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Delivery Order 0006: Airbreathing Propulsion Fuels and Energy Exploratory Research and Development (APFEERD)

Subtask: Review of Bulk Physical Properties of Synthesized Hydrocarbon: Kerosenes and Blends

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Interim Report

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14. ABSTRACT

This report compares the data on physical properties of synthesized hydrocarbon fuels and their blends with those of conventional Jet A/Jet A-1/JP-8 fuels to look for opportunities to safely reduce the amount of fit-for-purpose testing defined in ASTM D4054 in the approval process of synthesized kerosenes for use in jet fuel. The comparisons showed that for each property, the temperature dependencies and range of values are the same for all of the fuels, regardless of whether they were synthesized or natural. The evaluation concludes, based on fundamental physical chemistry, that all hydrocarbon kerosenes that meet the minimum density requirement will have bulk physical properties that are typical of conventional jet fuels regardless of resource or processing. These results lay the groundwork for combining all synthesized kerosenes into only a few Annexes in ASTM D7566 without regard to resource or processing.

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All conclusions and recommendations are those of the author and not necessarily those of UTC or the US Air Force.

1.0 SUMMARY

Since 1997, close to 40 synthesized kerosenes and blends thereof with conventional jet fuel have been evaluated to determine if they are fit-for-purpose either as blending streams for making jet fuel or as fully synthetic jet fuels. As interest has grown in the use of renewable resources for producing jet fuel, there have been complaints from the producers about the time and cost of approving these products for use. Alternately, the Original Equipment Manufacturers (OEMs) have complained about the number of potential fuels and the time that the approval process is taking away from their primary function as an equipment manufacturer. This report compares the data on physical properties of synthesized hydrocarbon fuels and their blends with those of conventional Jet A/Jet A-1/JP-8 fuels to look for opportunities to safely reduce the amount of fit-for-purpose testing defined in ASTM D4054 in the approval process of synthesized kerosenes for use in jet fuel. Such information could also increase the confidence in these fuels and ease the burden of reviewing the technical reports by the OEMs.

The investigation focused on the temperature dependencies of density, viscosity, specific heat, thermal conductivity, speed of sound, bulk modulus, and surface tension. The comparisons showed that for each property, the temperature dependencies are the same for all of the fuels, regardless of whether they were synthesized or natural. All of the properties are linear functions of temperature with the exception of isentropic bulk modulus which has a slight curvature due to a second-order dependency on the speed of sound. Moreover, if the synthesized fuels or blends contained sufficient aromatics to meet the minimum density requirements of jet fuel, then these properties for the synthesized fuels and blends had values that were typical of conventional jet fuels. Further comparison of these same properties for pure hydrocarbons showed the same temperature dependency regardless of carbon number or hydrocarbon family, i.e., n-paraffins, iso-paraffins, cyclo-paraffins, or aromatics. Comparisons of dielectric constant, air solubility, and water solubility showed similar results.

Detailed hydrocarbon composition of the fuels in the Coordinating Research Council (CRC) World Fuel Survey are included in this report to demonstrate the varied chemistry of the fuels in the survey and, thus, within the experience factor of jet fuels.

The evaluation concludes, based on fundamental physical chemistry, that all hydrocarbon kerosenes that meet the minimum density requirement will have bulk physical properties that are typical of conventional jet fuels regardless of resource or processing. These results lay the groundwork for combining all synthesized kerosenes into only a few Annexes in ASTM D7566 without regard to resource or processing.

A recommendation is made to evaluate the synthesized fuels for other properties in the ASTM D4054 fit-for-purpose protocol, particularly in the area of materials compatibility, to broaden the conclusions of this study to all of the properties in the protocol thus offering an opportunity to reduce the time and costs in approving new synthesized kerosenes for use in jet fuel. (Note that the conclusions of this report are limited to kerosene-type fuels and not to fuels of only one or two carbon numbers or to single compounds.)

2.0 INTRODUCTION

2.1 Background

Close to 40 synthesized kerosenes and blends thereof with conventional jet fuel have been evaluated over the last 16 years starting with the Sasol Iso-Paraffinic Kerosene (IPK), the first synthesized kerosene approved for use in commercial or military aviation under DEF STAN 91-91 Issue 3.[1] The restrictions place on the fuel were that it could be blended to a maximum of 50 v% providing the aromatic content was greater than 8 v%; all other fuel specifications for the final product had to be met, of course. The elements of the approval process were reviewed and refined a little for the approval of the Sasol Fully Synthetic Jet Fuel (FSJF) approved under DEF STAN 91-91 Issue 6 in February 2008.

In 2009, the approval protocol that had been used for the Sasol fuels was further refined and codified and then issued as ASTM D4054 *Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives*.[2] This protocol identifies the important properties and characteristics of jet fuels in the areas of:

- Chemistry
- Bulk physical and performance properties
- Electrical properties
- Ground handling and safety properties
- Compatibility with materials, additives, and other fuels

The protocol further provides guidance on values and limitations on these properties and characteristics for the candidate fuel to be considered fit-for-purpose. Based on the results of these laboratory tests, the engine and airframe OEMs may then identify component and/or engine tests to confirm the candidate fuel, or its blend with conventional fuel, is “fit-for-purpose” as a jet fuel.

The blending and approval of the final fuel is defined in ASTM D7566 *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*.[3] Fuels that have gone through the approval process are defined in Annexes to D7566 according to their resources and processes. Annex 1, defining the use of Synthesized Paraffinic Kerosenes (SPK) from Fischer-Tropsch processes, was included with the initial approval of D7566. It was another two years before SPKs processed from Hydrotreated Esters and Fatty Acids (HEFA) were approved in Annex 2; these fuels were identical to the fuels of Annex 1 in chemistry and physical properties. Fuels from many other resources and processes have been introduced since then, but it was another three years before a third Annex was approved using a lower concentration of only 10%(vol), necessitated by viscosity concerns. At least a half-dozen other fuels/processes have been engaged in the approval process, some for several years despite similarity of product.

At the 2014 meeting of the Commercial Aviation Alternate Fuels Initiative (CAAFI), frustration was exhibited by many of the prospective producers complained about the time and cost of the approval process. The following statements to that effect were included in the meeting summary by Mark Rumizen at the 2014 CRC Aviation Meeting:

- “ASTM D4054 Process too lengthy and costly”
- “Extensive fuel property and engine/aircraft testing”

- "Repeating same tests regardless of compositional similarities with previous fuel approvals"

The recommendation was that the industry should look for ways to safely reduce cost without sacrificing fuel quality and the effects on flight safety, air worthiness, durability, and maintenance.

2.2 Objective

The Objective of this report is to compare the data on physical properties of synthesized hydrocarbon fuels and their blends with conventional Jet A/Jet A-1/JP-8 fuels. The purpose is to look for opportunities to safely reduce the amount of fit-for-purpose testing defined in ASTM D4054 in the approval process of synthesized kerosenes for use in jet fuel.

2.3 Scope

The synthesized fuels and blends reviewed in this report are those fuels which have undergone a formal review process by the aviation fuel community and for which formal reports are available. Reported data were found for a total of 40 synthesized hydrocarbon fuels and/or their blends with conventional jet fuels. These fuels are broken into three categories:

1. Fischer-Tropsch (F-T) processed fuels from synthesis gas, e.g., Synthesized Paraffinic Kerosenes (SPK) and Sasol Fully Synthetic Jet Fuel (FSJF)
2. Hydroprocessed Ethers and Fatty Acids (HEFA)
3. Other renewables, e.g., alcohol to jet (ATJ), Hydrotreated Depolymerized Cellulosic Jet (HDCJ), and Catalytic Hydrothermolysis (CH). These fuels require individual approval ant are sometimes called "2nd-generation" renewable fuels.

The primary properties of comparison are the bulk physical properties identified in Table 1 of ASTM D4054-09. These properties are as follows:

- Density vs. temperature
- Specific heat vs. temperature
- Kinematic viscosity vs. temperature
- Surface tension vs. temperature
- Thermal conductivity vs. temperature
- Speed of sound vs. temperature
- Isentropic bulk modulus vs. temperature
- Dielectric constant vs. temperature
- Dielectric constant vs. density
- Water solubility vs. temperature

In general, three comparisons are made for these properties:

1. The properties of the synthesized fuels and/or blends are compared with each other to show commonality of synthesized products regardless of resource or process
2. These same properties are compared with the properties of petroleum-derived Jet A/Jet A-1/JP-8 fuels to show similarity with conventional jet fuels
3. These same properties are compared with the properties of pure hydrocarbons in the jet fuel boiling range to show that the similarities found in the first two comparisons are based on fundamental physical chemistry, independent of resource or process.

Table 1 identifies the fuels and the bulk physical properties that are compared in this report. An "X" indicates a property for each fuel that is a part of the comparison. (Note: Other data may exist but had not been located at the time of this writing.)

Table 1. Summary of Fuels and Properties Compared

Fuel	Property	Ref.	Density vs. T	Kinematic Viscosity vs. T	Surface Tension vs. T	Specific Heat vs. T	Thermal Conductivity vs. T	Dielectric Constant vs. T	Dielectric vs. Density	Speed of Sound vs. T	Bulk Modulus vs. T	Water Solubility vs. T
Reference Fuels	CRC WFS	[4]	X	X	X	X		X	X	X		
	CRC Handbook	[5]	X	X	X	X	X	X			X	
	EASA	[6]										X
F-T Fuels	Sasol IPK	[7.8]	X	X	X		X	X	X	X	X	
	Sasol IPK/Jet A-1	[7]	X	X	X	X	X	X	X	X	X	
	Syntroleum S-8	[7,9]	X	X	X	X	X	X	X	X		
	Syn. S-8/JP-8	[7,9]	X	X	X	X	X	X	X		X	
	Shell GTL	[7,9]	X	X	X		X	X	X			
	Shell GTL/JP-8	[7,9]	X	X	X	X	X	X	X		X	
	Sasol GTL-1	[7]	X	X	X	X		X	X			
	Sasol GTL-1/Jet A	[7]	X	X	X	X		X	X		X	
	Sasol GTL-2	[7]	X	X	X	X						
	Sasol GTL-2/Jet A	[7]	X	X	X	X		X	X		X	
	Sasol FSJF-1	[10]	X	X	X	X	X	X	X	X	X	
	Sasol FSJF-2	[10]	X	X	X	X	X	X	X	X	X	
	Sasol FSJF-3	[10]	X	X	X	X	X	X	X	X	X	
	Sasol FSJF-4	[10]	X	X	X	X	X	X	X	X	X	
	Sasol IPK/A	[11]	X	X	X	X	X	X	X			X
	Renjet	[12]	X	X								
	Renjet/JP-8	[12]	X	X	X	X	X	X	X	X	X	X
HEFA	FER-1	[8,13]				X						
	UOP-1	[8,13]		X		X		X				
	UOP-2	[8,13]		X		X		X	X	X		X
	UOP-2B50	[8,13]	X	X	X	X		X	X		X	X

Fuel	Property	Ref.	Density vs. T	Kinematic Viscosity vs. T	Surface Tension vs. T	Specific Heat vs. T	Thermal Conductivity vs. T	Dielectric Constant vs. T	Dielectric vs. Density	Speed of Sound vs. T	Bulk Modulus vs. T	Water Solubility vs. T
	UOP-3	[8,13]		X		X		X	X	X		X
	UOP-3B50	[8,13]	X	X	X	X		X	X		X	X
	UOP-4	[8,13]		X		X		X	X	X		X
HEFA (cont.)	UOP-4B50	[8,13]	X	X	X	X		X	X		X	X
	UOP-5	[8,13]		X	X	X		X	X			X
	UOP-5B50	[8,13]		X	X	X		X	X			X
	R-8	[8,13]	X	X	X	X	X	X	X	X	X	
	R-8/JP-8	[8,13]	X	X		X	X	X	X			
Other Renew-ables	NExBTL	[14]	X	X	X	X	X	X	X	X	X	X
	Gevo ATJ	[14]	X	X			X					
	GEVO/JP-8	[14]	X	X	X	X	X	X	X	X	X	X
	ARA/JP-8	[14]	X	X	X	X	X	X	X	X	X	X
	KiOR/Jet A (30/70)	[14]	X	X	X	X	X	X	X	X	X	X
	SBF/JP-8	[14]	X	X	X	X	X	X	X	X	X	X
	Virent/JP-8	[14]	X	X	X	X	X	X	X	X	X	X
	Amyris/JP-8	[14]	X	X	X	X	X	X	X	X	X	X

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Overview of the Presentation

Most of the physical properties are available for all of the fuels. Each of the properties will be presented for comparison in a collection of four graphs with the exception of thermal conductivity; thermal conductivity data are not available for many of the fuels, so they will be presented in only two graphs. In each of the other presentations:

1. The first graph will be property data for fuels in the CRC World Fuel Survey (WFS).[4] For the sake of clarity in the graph, only the 31 Jet A/Jet A-1/JP-8/JP-5 fuels from North America are presented; otherwise there would be so much overlap that they lines would be indistinguishable. (Note: Survey Fuel #36, Stoddard Solvent, was not included because it is not a real jet fuel.)
2. The second graph presents the data for F-T and HEFA SPKs approved under Annexes 1 and 2 of D7566. Also included are the Sasol Fully Synthetic Jet Fuels (FSJF) and Sasol IPK/A, which have their origin in F-T processes, but also contain synthesized aromatics.
3. The third graph presents data for the 2nd-generation renewable fuels synthesized by processes other than F-T and HEFA.
4. The fourth graph presents property data for pure C10 hydrocarbons – n-paraffins, iso-paraffins, cyclo-paraffins, and aromatics, to demonstrate that all hydrocarbons have essentially the temperature dependence for each property; thus, the results for the fuels are not somehow coincidental, but are related to fundamental physical chemistry. With the exception of surface tension and dielectric constant, the data for pure hydrocarbons were obtained using the software program SUPERTRAPP [15] developed by the National Institute of Standards and Testing (NIST); this program calculates thermodynamic and transport properties of pure hydrocarbons as functions of temperature and pressure. Data for surface tension and dielectric constant of pure hydrocarbons were taken from the CRC Handbook of Chemistry and Physics.[16,17]

In addition, for the properties of density and specific heat, data are presented separately for each of the four hydrocarbon families for molecules ranging from C8 to C12 to show that the characteristics presented for C10 hydrocarbons are true for other carbon numbers as well.

Of the properties evaluated in this report, only the density and viscosity are controlled by the fuel specifications. The limits are provided in the graphs for these properties to show conformance.

In these presentations, it has sometimes been necessary to change the vertical scales due to the range of the data and the desire to separate the lines as much as possible for clarity. In each case, a reference line, from the CRC WFS fuels and/or for the CRC Handbook [5], are provided so that the reader can see the commonality of the data. Since the individual graphs are necessarily somewhat small in order to make the four-graph comparisons, larger versions of each graph are provided in Appendix 1.

In the matter of nomenclature, the term “kerosene” will be used extensively to mean a distillate fraction that is typical of jet fuels, i.e., one that covers many contiguous carbon numbers and is comprised of many isomers in each of the hydrocarbon families. This is in contrast to a hydrocarbon fuel that is more like a solvent or pure hydrocarbon in that it is basically one or two carbon numbers or even just a few isomers.

Finally, the reader is cautioned that the discussions of the figures will get quite repetitive since, for each property, all the fuels have very similar temperature dependence.

3.2 Thermodynamic and Transport Properties

3.2.1 Density vs. Temperature

Density characteristics are presented in Figure 1. Figure 1-a presents the density data for the fuels from the WFS. The density data are linear with temperature and are essentially parallel to each other. The density data line for Jet A/JP-8 from the CRC Handbook has a slightly different slope, which is not thought to be significant. The densities for all the fuels lie within the specification limits at 15°C of 775 to 840 kg/m^3.

Figure 1-b presents the density data for the F-T and HEFA fuels and their blends. Like the conventional fuels of Figure 1-a, these data are linear with temperature and essentially parallel to each other and to the reference data lines for the WFS fuels of Figure 1-a. The density lines for many of the fuel blends lie below the range of the WFS fuels but are above the specification minimum; the lower density is to be expected since these blends typically have only 8 to 10 vol% aromatics. The data lines that lie below the specification minimum are the neat synthesized kerosenes which contain no aromatics, with one exception: The Shell GTL had a very low density and was blended with a rather light JP-8 at a ratio of 50/50 without regard to minimum density. Note that all the neat synthesized kerosenes had the same temperature dependence as the blends and conventional fuels.

Figure 1-c presents the density data for the more recent fuels from renewable sources. These data are very similar to those of Figure 1-b: linear and parallel to each other as well as the WFS data of Figure 1-a. Some of the neat fuels in this set contain aromatics and, therefore, meet the specification minimum density without blending.

Figure 1-d presents the density data for pure hydrocarbons in all four families. As previously stated, only hydrocarbons with 10 carbon atoms are shown for clarity. Here, too, the lines are linear and parallel with each other as well as with those of the WFS fuels. Note that the densities of the normal- and iso-paraffins all lie below the CRC Handbook value for a typical jet fuel; while the densities of the aromatics lie well above.

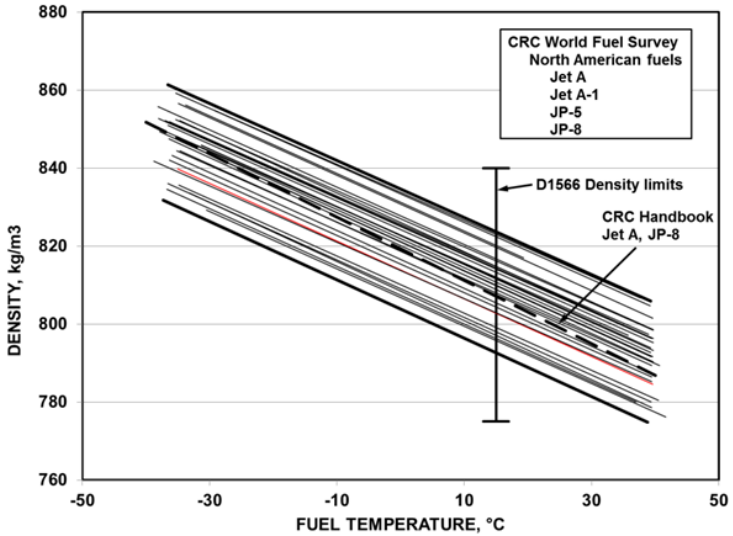


Figure 1-a. CRC World Fuel Survey

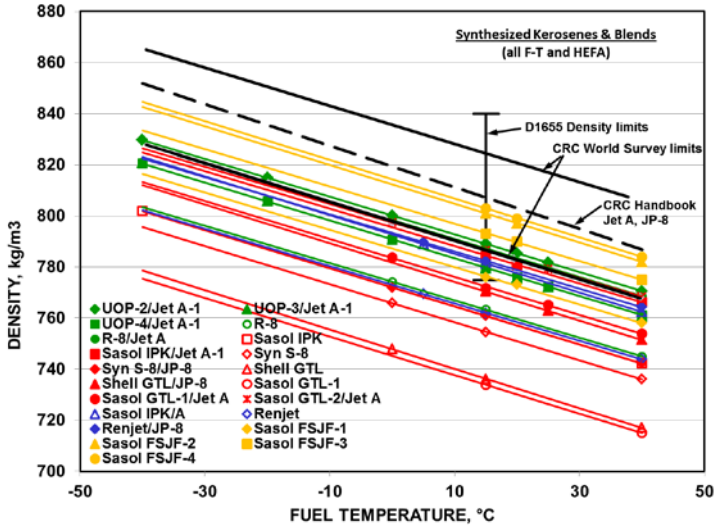


Figure 1-b. F-T and HEFA Fuels and Blends

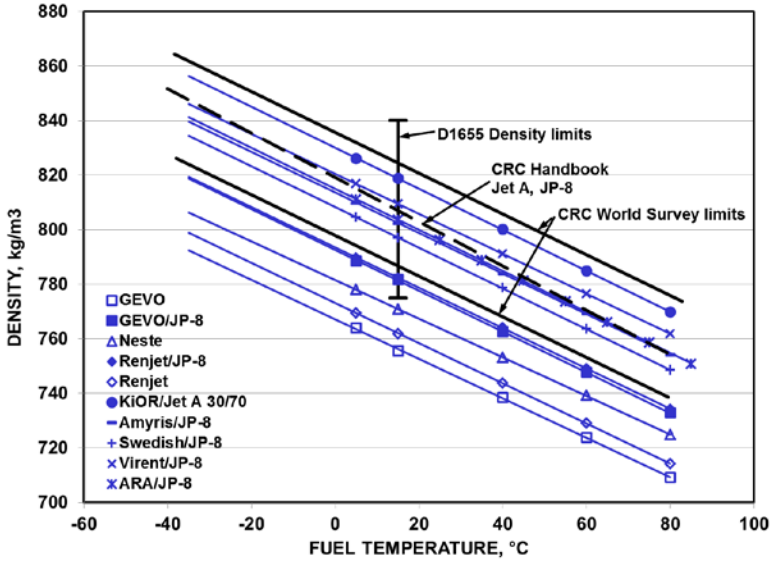


Figure 1-c. 2nd Generation Renewable Fuels and Blends

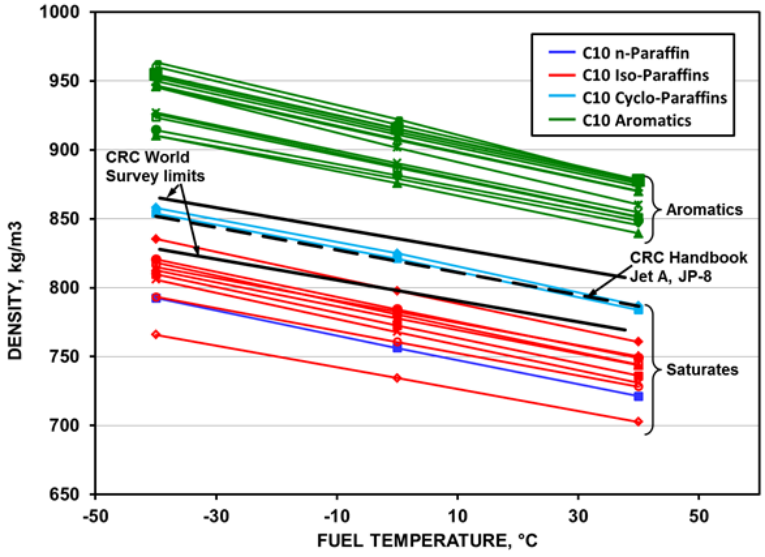


Figure 1-d. Pure C10 Hydrocarbons

Figure 1. Density of Hydrocarbon Fuels

The above observation on the density of pure hydrocarbons are further supported and generalized by the four graphs of Figure 2. These graphs present the densities of pure hydrocarbons for each of the four hydrocarbon families as functions of temperature for carbon numbers ranging from C8 to C12. The data on the graphs of Figure 2 demonstrate several important points:

1. Density is linear with temperature for all hydrocarbons, and the variations in slope are minimal.
2. Density increases with carbon number.
3. Aromatics are important to meet minimum fuel density unless the fuel has a high concentration of cyclo-paraffins.
4. The presence of aromatics does not change the temperature sensitivity of the fuel, whether synthesized or natural.

From these data, it is concluded that the density values and characteristics of all synthesized hydrocarbon kerosenes and their blends are typical of conventional jet fuels regardless of resource or process.

3.2.2 Specific Heat vs. Temperature

Figure 3 presents the characteristics of specific heat. Figure 3-a presents the specific-heat data of the WFS fuels. With a few exceptions, the data lines are parallel and very similar to the data line for Jet A/Jet A-1/JP-8 from the CRC Handbook. Concern has been expressed about the validity of these data because, while the slopes are very similar to the CRC Handbook data, the values seem to be too low.[13]

Figure 3-b presents the specific-heat characteristics for the F-T and HEFA fuels and blends. Although these data are linear and parallel to each and to the CRC reference line, with a few exceptions, there seems to be a problem with these data as well, although the problem is different. In addition to some of the F-T data seeming to be low, the data for the HEFA blends with conventional fuel, which contain aromatics, seem to be too high. This will be discussed further a few paragraphs hence.

Figure 3-c presents the specific-heat characteristics for the more recent renewable fuels. Again, the data are linear and parallel to each other and to the CRC Handbook data. The data for these graphs were obtained with an improved method and, as a result, the data lines are closer to the CRC Handbook data and seem more reasonable than those in the previous two graphs.

Figure 3-d presents the specific heat characteristics for pure C10 hydrocarbons and begins to explain the concern over the data for the CRC WFS fuels in Figure 3-a and the F-T and HEFA fuels of Figure 3-b. The specific heats for C10 normal and iso-paraffins are on the order of 5-10% higher than the Handbook data, while the data for the C10 aromatics are on the order of 10-20% lower. The one data line for a cyclo-paraffin is lower than the Handbook data, but not as low as the aromatics. The specific heat of naphthalene is lower than the single-ring aromatics.

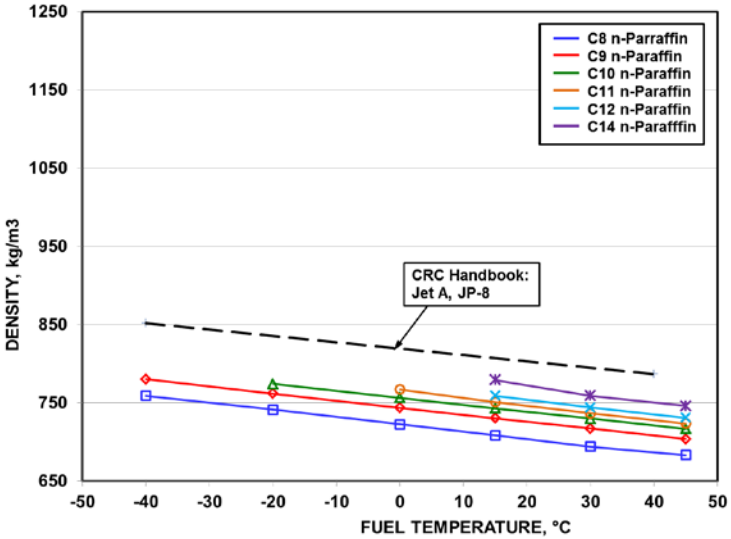


Figure 2-a. Density of n-Paraffins

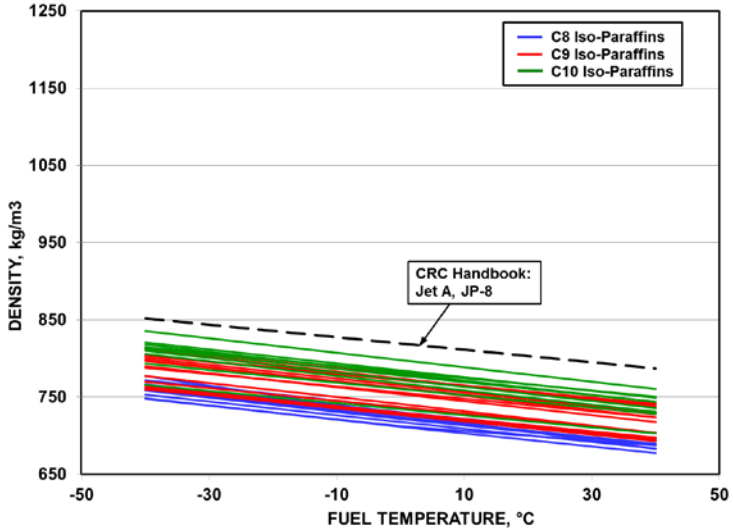


Figure 2-b. Density of Iso-Paraffins

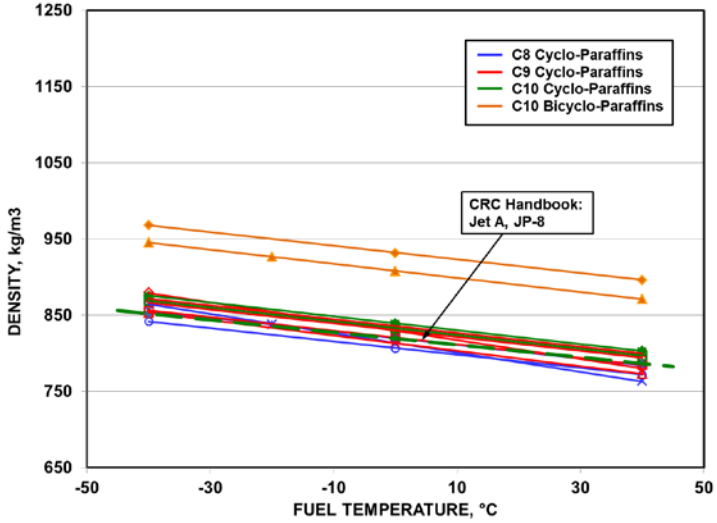


Figure 2-c. Density of Cyclo-Paraffins

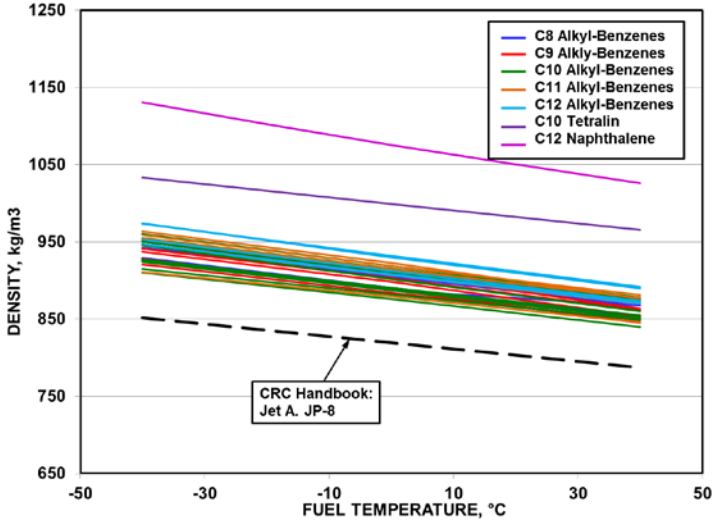


Figure 2-d. Density of Aromatics

Figure 2. Density of Pure Hydrocarbons

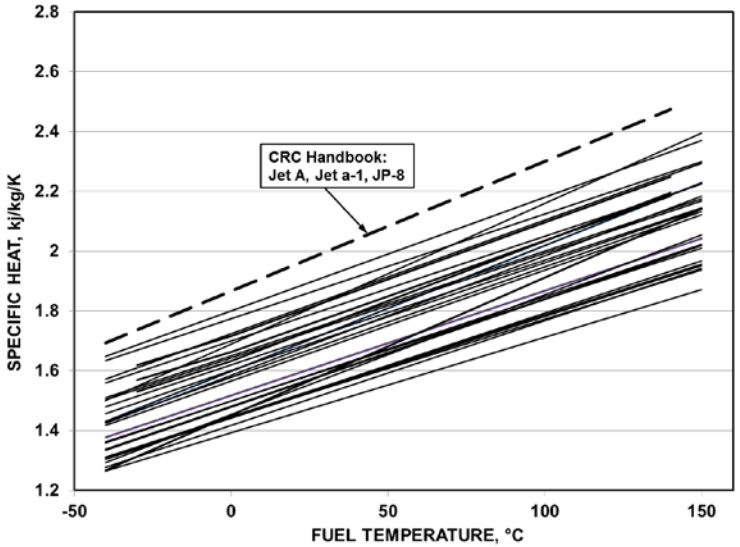


Figure 3-a. CRC World Fuel Survey

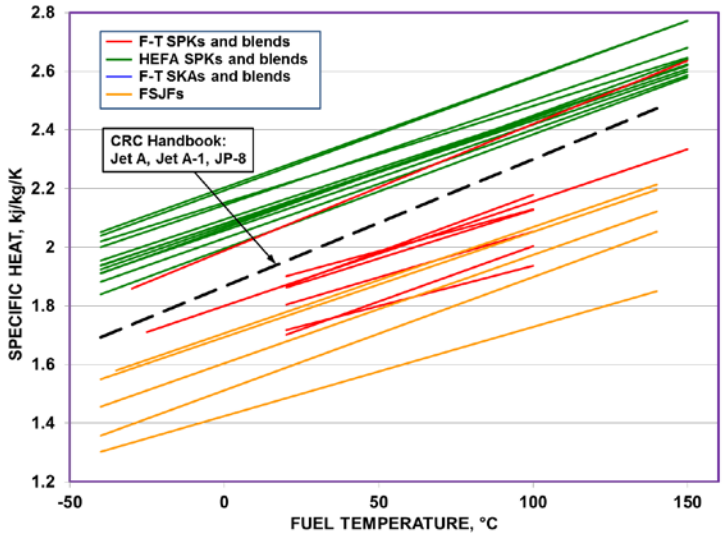


Figure 3-b. F-T and HEFA Fuels and Blends

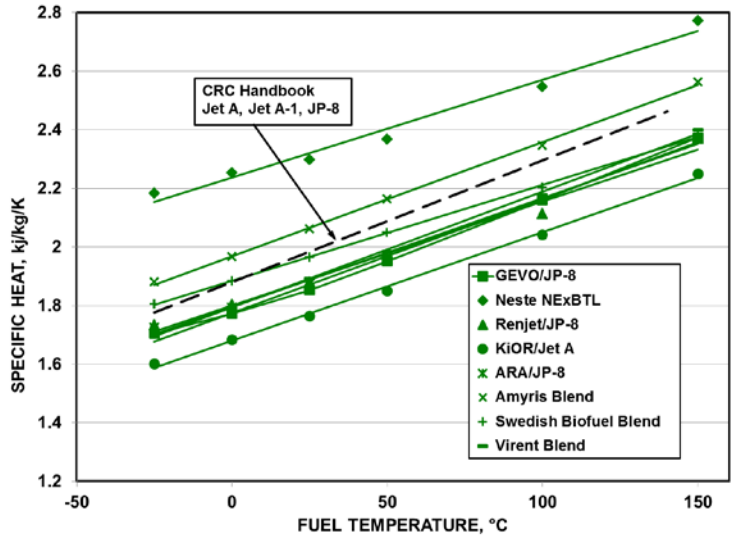


Figure 3-c. 2nd Generation Renewable Fuels and Blends

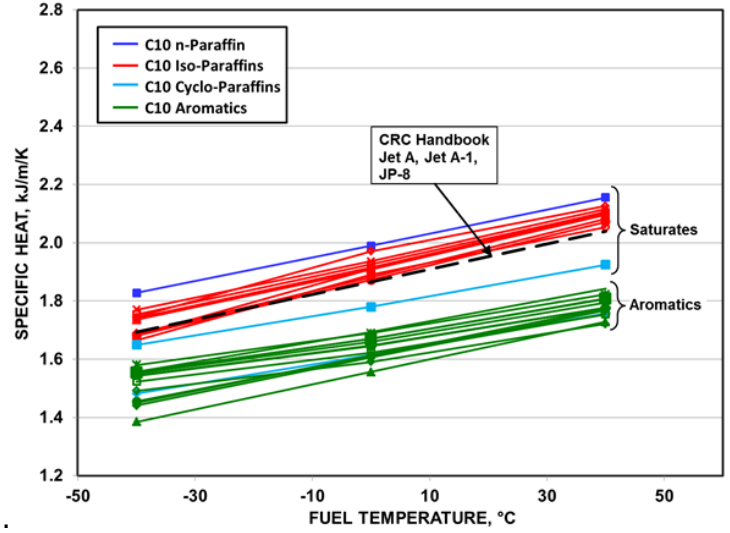


Figure 3-d. Pure C10 Hydrocarbons

Figure 3. Specific Heat of Hydrocarbon Fuels

Due to this question about the values of specific heat of the WFS, F-T, and HEFA fuels, it is worthwhile to consider the specific heat of more than just the C10 hydrocarbons to get a better sense of the possible range of values for specific heat of kerosenes. The four graphs of Figure 4 present the specific-heat characteristics of the four hydrocarbon families. The normal and iso-paraffins have the highest specific heats and general overlap each other. From these data, it would be difficult to have a specific heat greater than 2.0 kJ/kg/K at 0°C, even for a totally paraffinic fuel. The presence of cyclo-paraffins and aromatics reduces the specific heat, but a totally aromatic fuel would have a specific heat greater than 1.6 kJ/kg/K at 0°C, unless there were also cyclo-aromatics and naphthalenes present which have specific heats less than the alkyl benzenes shown in Figure 4-d.

The data in Figure 4 confirm the concern over the values of specific heat for the CRC WFS fuels and the F-T and HEFA fuels of Figure 3-a and 3-b. However, the data of Figure 4 further confirm that the temperature sensitivities of all hydrocarbons are essentially the same and hence the slopes of the graphs in Figure 3 are correct. The data for the more recent renewable fuels in Figure 3-c seem reasonable, with the exception of the neat Neste product, which had been tested much earlier and was probably subject to the same problem as the HEFA fuels.

In summary, with respect to specific heat, it is safe to conclude that the temperature dependence of all synthesized hydrocarbon kerosenes and their blends are typical of conventional jet fuels regardless of resource or process. The exact problems with the analyses is not known, but it highly probable that the specific heats of all the fuels, whether conventional or synthesized and blended will be in the same range, depending only upon the aromatic and cycloparaffins content.

3.2.3 Kinematic Viscosity vs. Temperature

Kinematic viscosity, itself, is not linear with temperature. However, the ASTM has developed a transform function that allows kinematic viscosity data to be presented as linear functions. This function is defined in ASTM D341.[18] The viscosity data presented in the four graphs of Figure 5 have been transformed by this function.

Figure 5-a presents the kinematic viscosity data for the WFS fuels. As with the density data, the lines are parallel and very similar to the data line for Jet A/JP-8(US)/JP-5 from the CRC Handbook. All of the fuels have viscosities that are well under the specification maximum of 8.0 cSt @ -20°C; however, several fuels have viscosities greater than 12 cSt at -40°C, the operational limit for some engines and APUs.

Figure 5-b presents the data for the F-T and HEFA fuels and blends. Like the WFS fuels, the data lines are linear and parallel both to each other and to the reference lines, which are buried within the other data lines but indicated. Again, the viscosities of all the fuels meet the specification requirements. The only fuel to exceed 12 cSt at -40°C is the neat UOP-5 HEFA fuel; upon blending, the viscosity was acceptable at all temperatures.

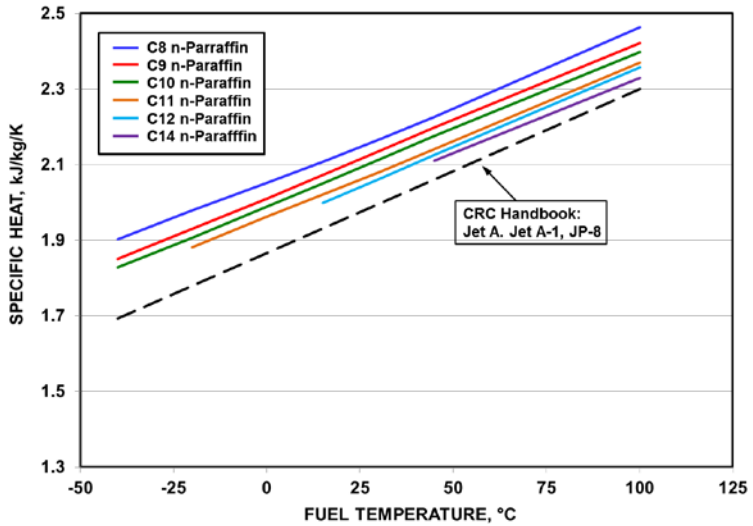


Figure 4-a. Specific Heat of n-Paraffins

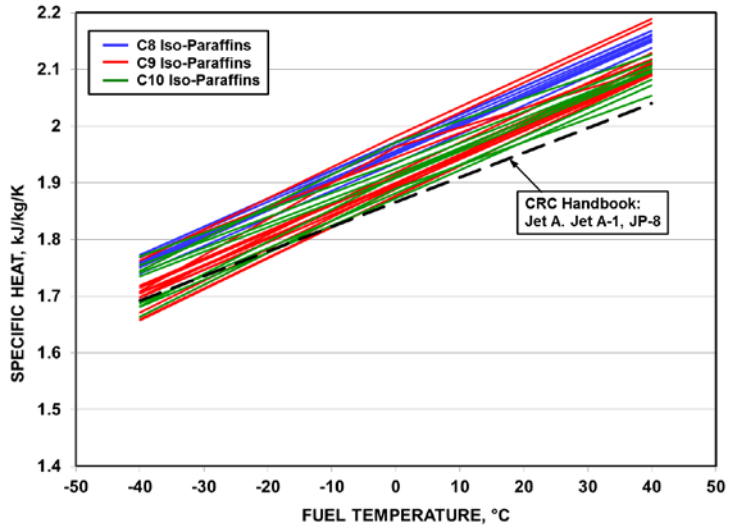


Figure 4-b. Specific Heat of Iso-Paraffins

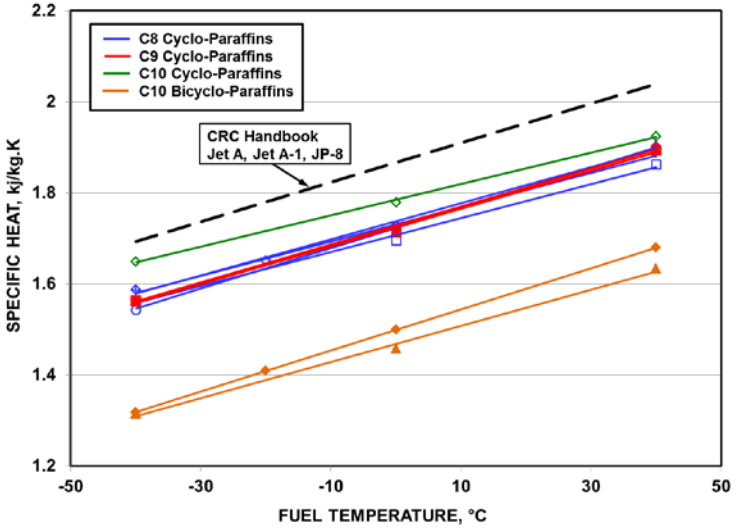


Figure 4-c. Specific Heat of Cyclo-Paraffins

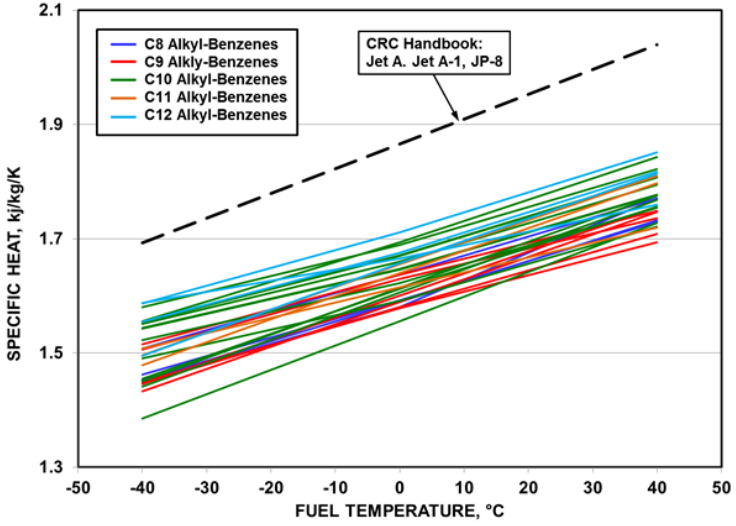


Figure 4-d. Specific Heat of Aromatics

Figure 4. Specific Heat of Pure Hydrocarbons

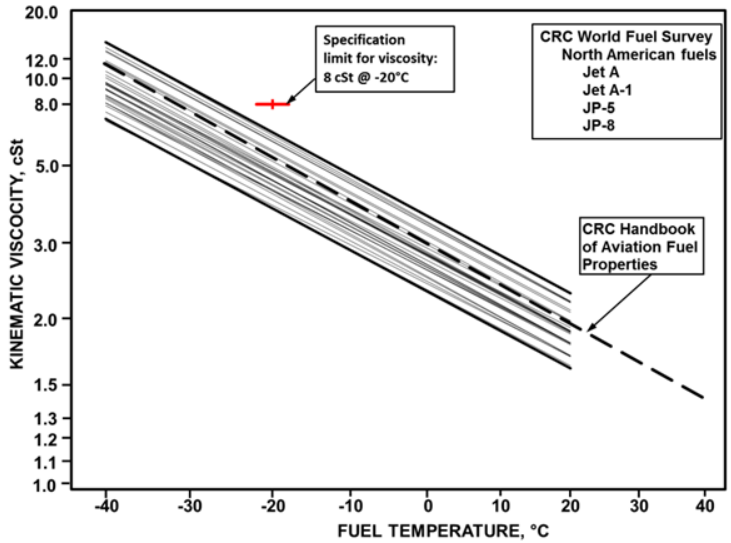


Figure 5-a. CRC World Fuel Survey

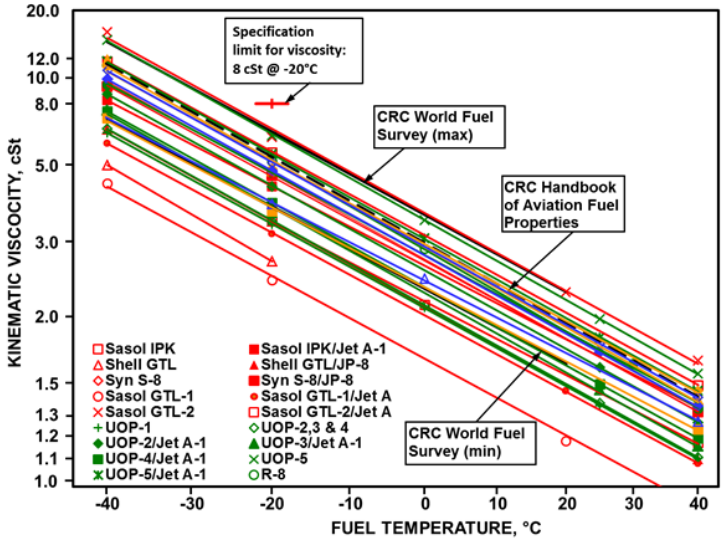


Figure 5-b. F-T and HEFA Fuels and Blends

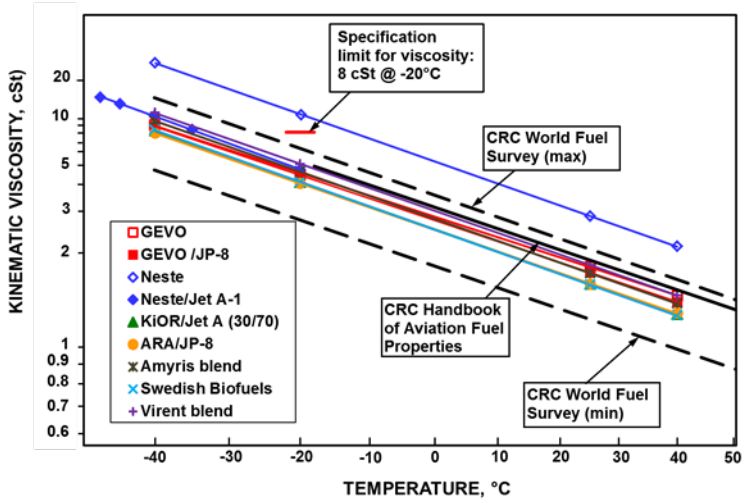


Figure 5-c. 2nd Generation Renewable Fuels and Blends

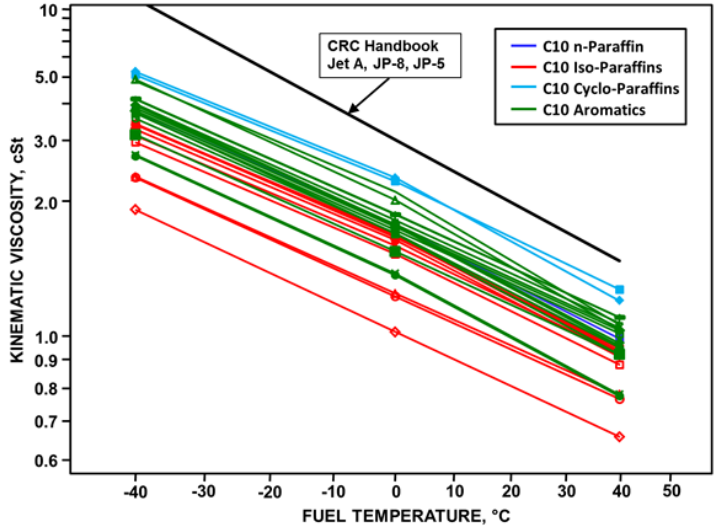


Figure 5-d. Pure C10 Hydrocarbons

Figure 5. Kinematic Viscosity of Hydrocarbon Fuels

Figure 5-c tells the same story for the other renewable fuels and their blends: the data lines are linear and parallel with each other and with the reference lines from the WFS and the CRC Handbook. The viscosity of the neat Neste product does not meet the maximum viscosity limit; however, the 50/50 blend with the Neste Jet A-1 has a viscosity of 5.1 cSt at -20°C, well under the specification limit.

Figure 5-d presents the kinematic viscosity characteristics for pure hydrocarbons in all four families. SUPERTRAPP calculates dynamic viscosity, μ, rather than kinematic viscosity, v; these properties are related by density, ρ, by $v = \mu/\rho$. While a few of the lines are not linear, they majority are linear and parallel to each other and very similar to the reference line from the CRC Handbook. Unlike the density characteristics, for viscosity, there is no clear separation among the hydrocarbon families. It is clear, however, that the viscosity characteristics of the aromatics are the same as the saturates.

From these data, it is concluded that the kinematic viscosity characteristics of all synthesized hydrocarbon kerosenes and their blends are typical of conventional jet fuels regardless of resource or process. Maximum viscosity will be controlled by the specification.

3.2.4 Thermal Conductivity vs. Temperature

The CRC WFS fuels were not analyzed for thermal conductivity. Figure 6-a presents the thermal conductivity data for all of the synthesized kerosenes and their blends. Figure 6-b presents the thermal conductivity data for the C10 hydrocarbons. Thermal conductivity is quite insensitive to temperature, changing only 10% or less in 50°C The data in Figure 6-a seem to fall into two sets; however, both sets contain a reference jet fuel, so the difference appears to be in the analysis not in the fuels. Thermal conductivity is known to be difficult to measure for liquids due to the potential for heat losses from diffusion and conduction and the need for accurate specific heat data, which has shown been shown to be suspect for the earlier fuels. Looking at the data for pure hydrocarbons, there does not seem to be a separation by hydrocarbon family. Thermal conductivity is linear with temperature and the data lines for the individual fuels and pure hydrocarbons are parallel. The CRC Handbook presents a common data line for all kerosene-type fuels.

The data for the fuels and the pure hydrocarbons are very similar in slope and range; thus, despite the fact that the fuel data seem to fall into two groups, it is apparent that all synthesized hydrocarbon kerosenes, whether or not they contain aromatics, have thermal conductivity values and characteristics that are typical of conventional jet fuel.

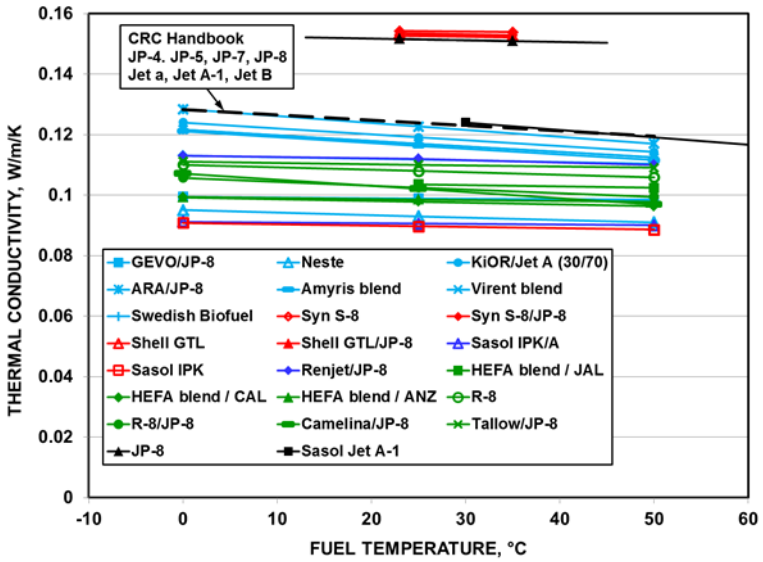


Figure 6-a. All Synthesized Fuels and Blends

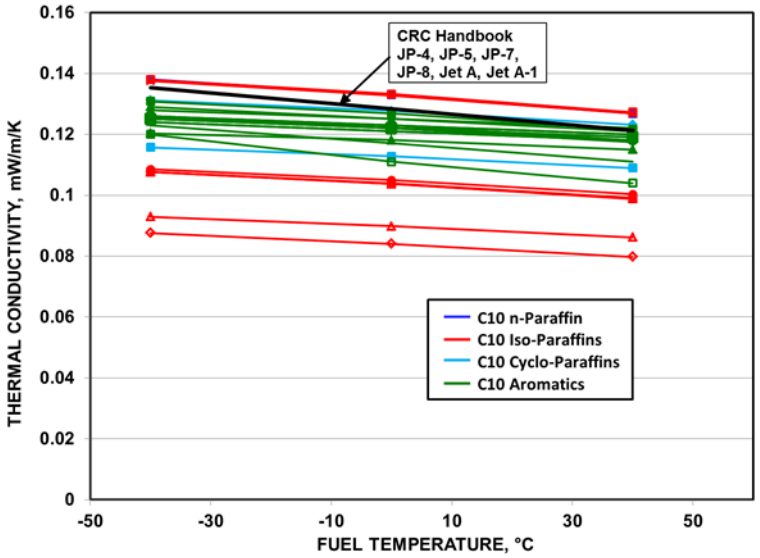


Figure 6-b. Pure C10 Hydrocarbons

Figure 6. Thermal Conductivity of Hydrocarbon Fuels

3.2.5 Speed of Sound vs. Temperature

The speed of sound, or acoustic velocity, in fuel is important for two reasons: fuel tank gauging and calculation of isentropic bulk modulus (see Section 3.2.6).

Figure 7-a presents the data on speed of sound for the CRC WFS fuels. In the summary report for this survey [1], the data for speed of sound at nominal temperatures above 0°C are missing; the data for the lower temperatures are presented twice. Because the data are linear with temperature, the data presented in Figure 6-a for temperatures above 0°C (nominal) are extrapolated. As with the earlier bulk properties, the speed of sound is linear with temperature and the lines for different fuels are essentially parallel. The CRC Handbook does not provide data for speed of sound; instead, an average data line from the CRC WFS is used as a reference line for the other 3 graphs in this set.

Figure 7-b presents the data on speed of sound vs. temperature for the F-T and HEFA fuels. The data for the HEFA fuels are not actual measurements but are calculated from isothermal bulk modulus data.[13] (See Section 3.2.6 for details.) The measured data for the F-T fuels are linear and parallel to each other as well as to the reference line from the CRC WFS.

Speed of sound data for the other renewable fuels are presented in Figure 7-c. For these fuels, measurements were taken only at a single temperature, 30°C, so a temperature function is not possible. With the exception of the neat GEVO fuel, the variation is about the same as for the F-T fuels of Figure 7-b. The Gevo fuel is comprised of essentially only C12 and C16 paraffins whereas the other fuels in this figure are blends and hence full boiling range. As shown in Figure 7-d, branching affects the speed of sound in n- and iso-paraffins.

Figure 7-d presents the speed of sound data for C10 hydrocarbons as calculated by SUPERTRAPP. There is a slight non-linearity in the data, but all the hydrocarbons have the same feature. Despite the slight non-non-linearity, the data lines are parallel to each other, and they are essentially parallel to the reference line from the CRC WFS data. Although there is some overlap, in general, the speed of sound is higher in aromatics than in saturates. The red and dark blue data lines demonstrate the effect of branching as mentioned in the previous paragraph: The speed of sound of n-decane is higher than any of the C10 iso-paraffins.

The speed of sound data for the fuels and the pure hydrocarbons are very similar in slope and range despite the slight non-linearity in the data for pure hydrocarbons. It is apparent that all synthesized hydrocarbon kerosenes, whether or not they contain aromatics, have speed-of-sound values and characteristics that are typical of conventional jet fuel.

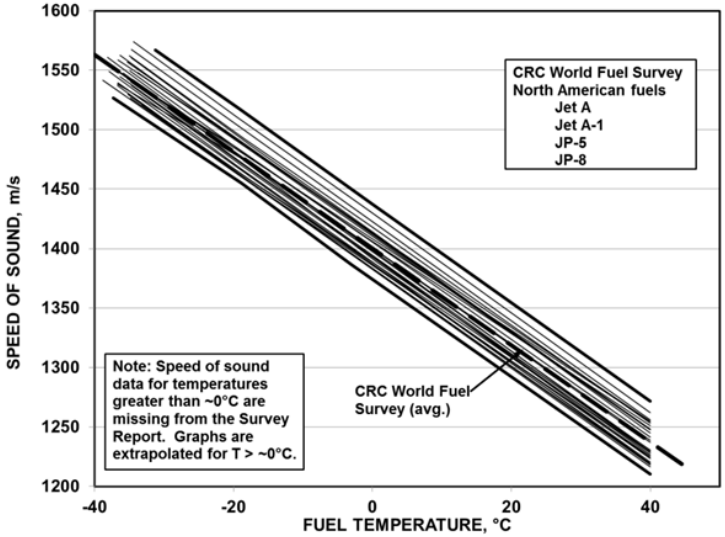


Figure 7-a. CRC World Fuel Survey

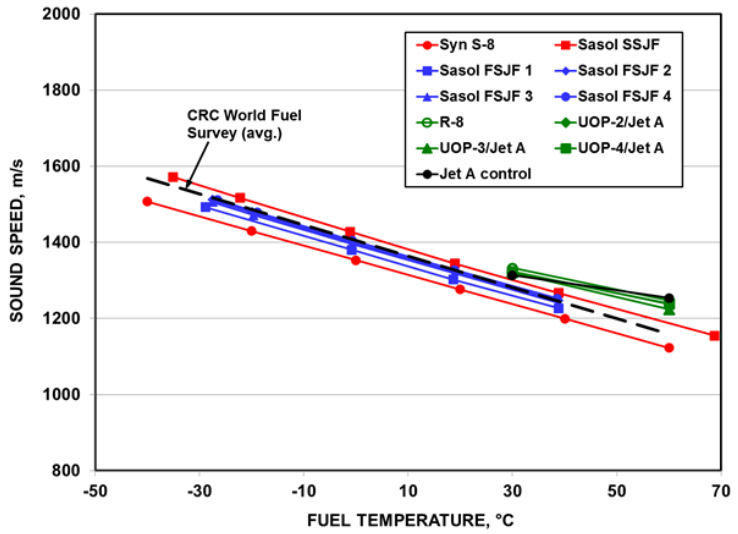


Figure 7-b. F-T and HEFA Fuels and Blends

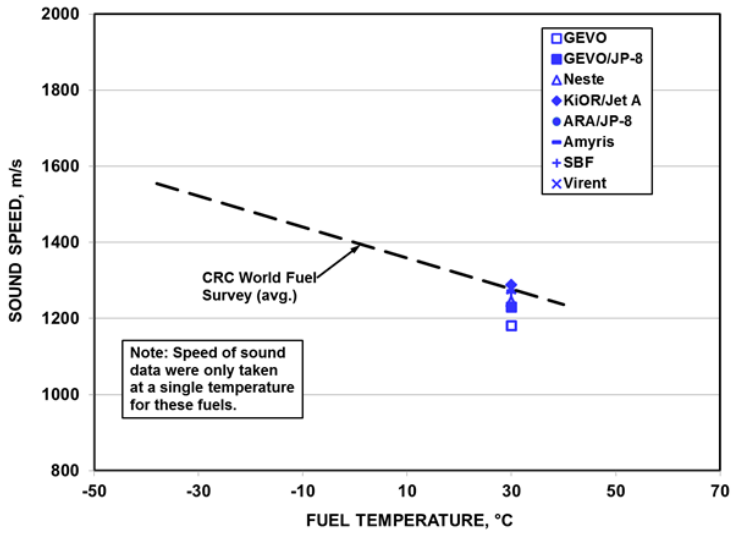


Figure 7-c. 2nd Generation Renewable Fuels and Blends

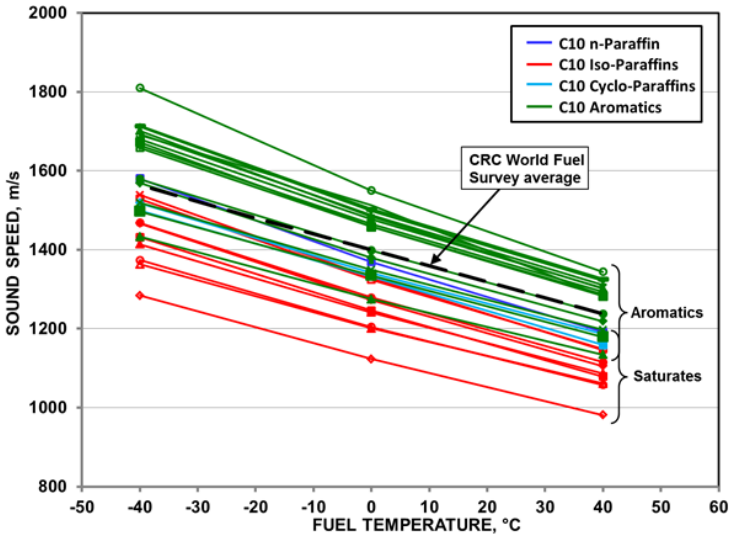


Figure 7-d. Pure C10 Hydrocarbons

Figure 7. Speed of Sound in Hydrocarbon Fuels

3.2.6 Isentropic Bulk Modulus vs. Temperature

Isentropic bulk modulus, β_S, is thermodynamically related to the density, ρ, and speed of sound, c, in the fluid by the relationship $\beta_S = \rho c^2$. This relationship was used to calculate the bulk modulus data presented in this section for all the fuels except the HEFA, R-8, and Sasol IPK fuels. Boeing reported values for the isothermal bulk modulus as measured by ASTM D6793 for the HEFA, R-8, and Sasol IPK fuels and calculated the isentropic bulk modulus, β_S, from the isothermal bulk modulus, β_T, using the thermodynamic relationship $\beta_S = \gamma\beta_T$, where γ is the ratio of specific heats, c_p/c_v. The CRC Handbook of Aviation Fuels gives a value for kerosene of γ = 1.15, but provides no reference. This relationship is valid for gases, but is open to question for liquids and solids since generally there is no distinction between c_p and c_v as these materials are essentially incompressible.

Figure 8-a presents the isentropic bulk modulus for the CRC WFS fuels as calculated from the data of Figures 1-a and 7-a. There is a slight curvature to the data due to the factor of c^2, but all the fuels have the same feature and the data functions are parallel to each other. An average data line is shown which is used as the reference line in the other three graphs of Figure 8.

Figure 8-b presents the data for the isentropic bulk modulus of the F-T and HEFA fuels. The F-T fuels, except for the Sasol IPK, show the same temperature characteristic as the WFS average, but are somewhat lower in value due primarily to their lower density. The data for the HEFA fuels, the Sasol IPK, and the associated reference Jet A appear to have similar characteristics, at least over the limited temperature range; however they are significantly separated from the other fuels. The values of isentropic bulk modulus for these fuels were calculated from the isothermal data as previously discussed. The ordering of these fuels is the same as for the F-T fuels – roughly according to density with the S-8 and IPK fuels having the lowest values. The fact that the data set containing the HEFA fuels exhibit higher values of bulk modulus suggests that either there was a problem with the measurements or the factor γ = 1.15 is too high as suggested earlier.

Figure 8-c presents values for isentropic bulk modulus for the other renewables as calculated from the data of Figures 1-c and 7-c. Since the data for speed of sound were taken at only one temperature, it is not possible to determine the temperature dependence for these fuels.

Figure 8-d presents the isentropic bulk modulus of C10 hydrocarbons as calculated from the values of Figures 1-d and 7d. Here, again, the temperature characteristics are similar to the reference line from the WFS fuels. It is obvious from this graph that the presence of aromatics increases the bulk modulus which means the fuel is more incompressible.

The isentropic bulk modulus for the fuels and the pure hydrocarbons are very similar in slope and range. Although the data are more limited than for most of the other properties, it is apparent that all synthesized hydrocarbon kerosenes, whether or not they contain aromatics, have bulk modulus values and characteristics that are typical of conventional jet fuel. The presence of aromatics makes the fuel more incompressible.

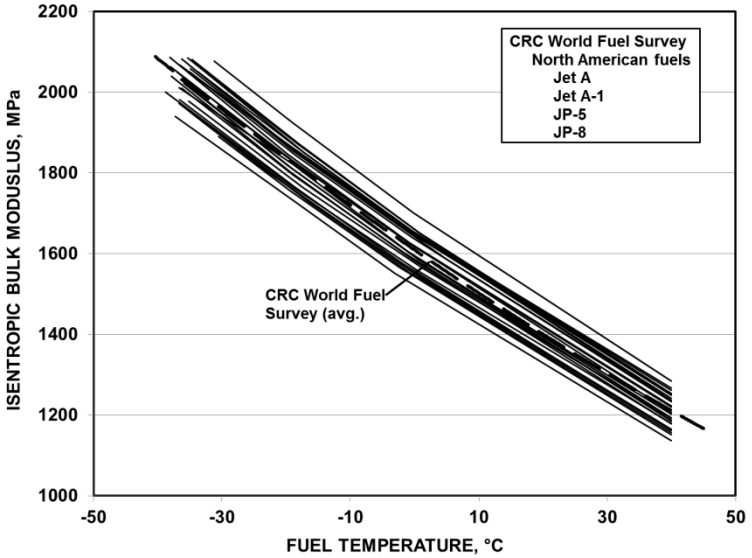


Figure 8-a. CRC World Fuel Survey

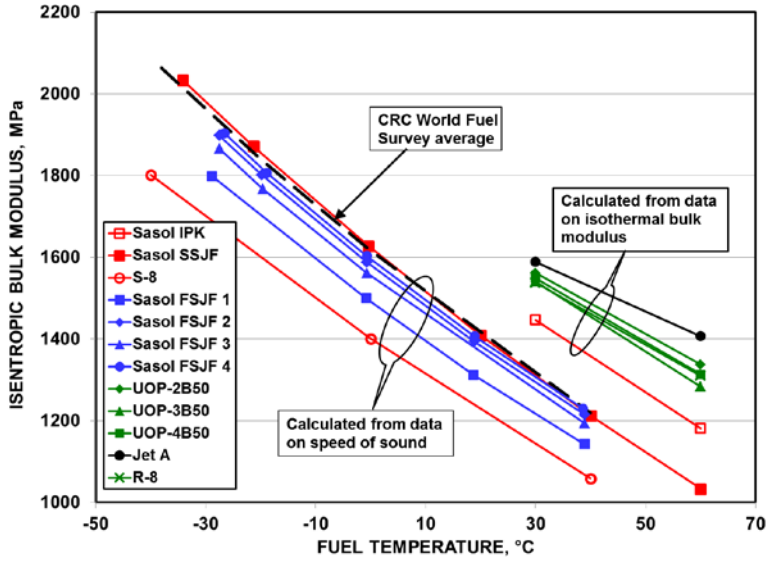


Figure 8-b. F-T and HEFA Fuels and Blends

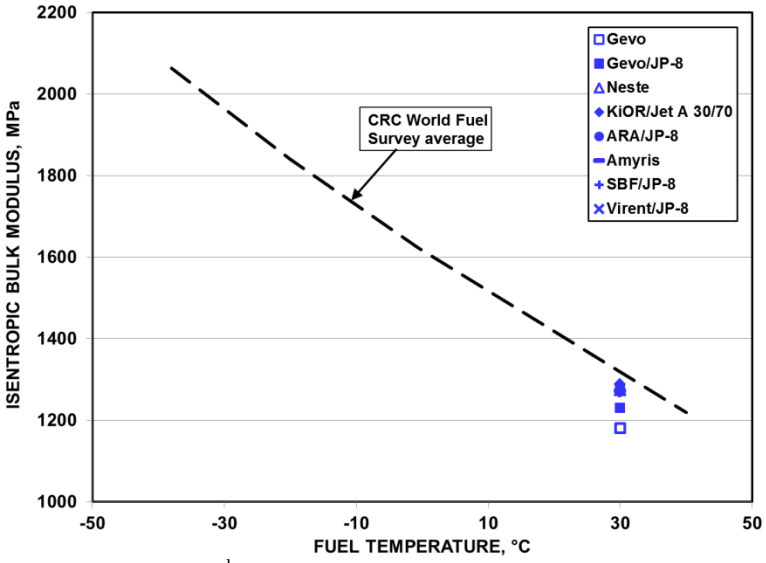


Figure 8-c. 2nd Generation Renewable Fuels and Blends

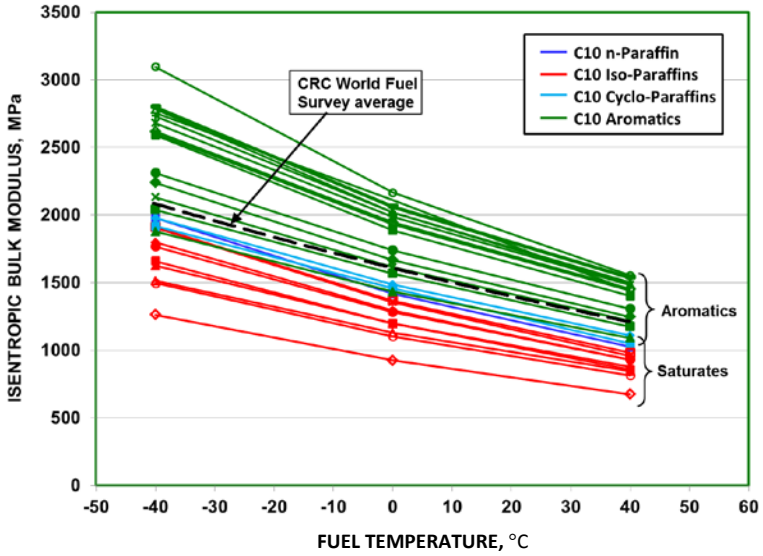


Figure 8-d. Pure C10 Hydrocarbons

Figure 8. Isentropic Bulk Modulus of Hydrocarbon Fuels

3.2.7 Surface Tension vs. Temperature

The temperature dependence of surface tension for the CRC WFS fuels is presented in Figure 9-a, and that of the F-T and HEFA fuels are presented in Figure 9-b. In both of these data sets, surface tension was measured at only two temperatures, so naturally the graphed lines are linear. They do, however, maintain the parallel nature of the previous property data. Since the surface tension data in the CRC Handbook are also linear with temperature, it is reasonable to assume this is true for the fuels in these two graphs. The surface tension data for the other renewables in Figure 9-c support this as the lines are linear least-square fits to the data; the lines are parallel and have a slope a little less than the CRC Handbook data.

The linear nature of the temperature dependence of surface tension is further supported by the data in Figure 9-d for pure hydrocarbons.[16] The surface tension data found for aromatics and iso- and cyclo-paraffins were very limited in carbon number, but the data for the normal paraffins ranges from C6 to C16, essentially the whole range of jet fuel. The data for pure hydrocarbons are all linear with temperature; the data for cyclo-paraffins and aromatics have a slightly greater slope. The data for the pure hydrocarbons cover the range of the jet fuels, so it is reasonable that the surface tension of complete fuels is linear with temperature.

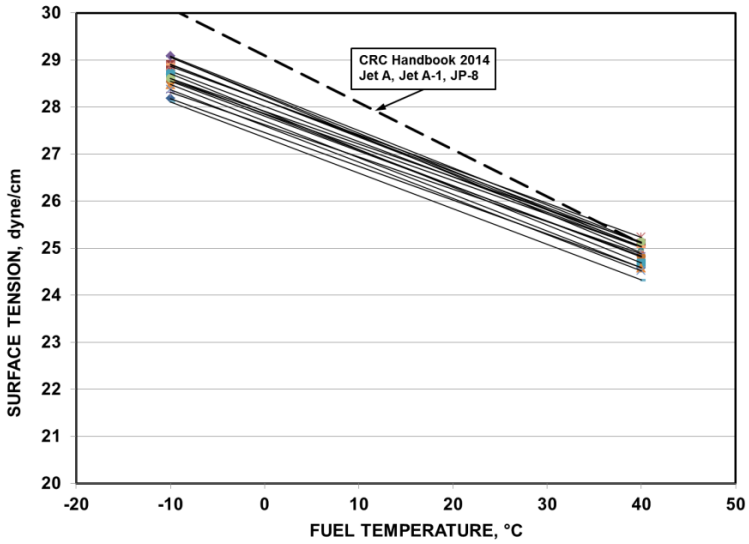


Figure 9-a. CRC World Fuel Survey

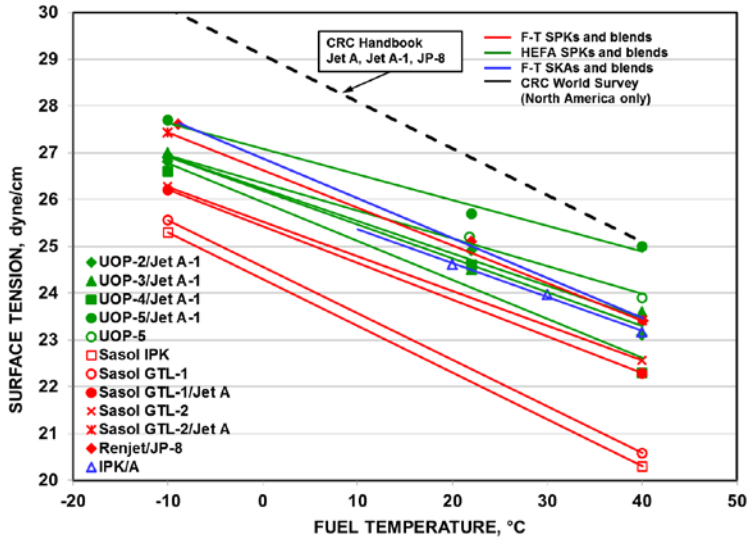


Figure 9-b. F-T and HEFA Fuels and Blends

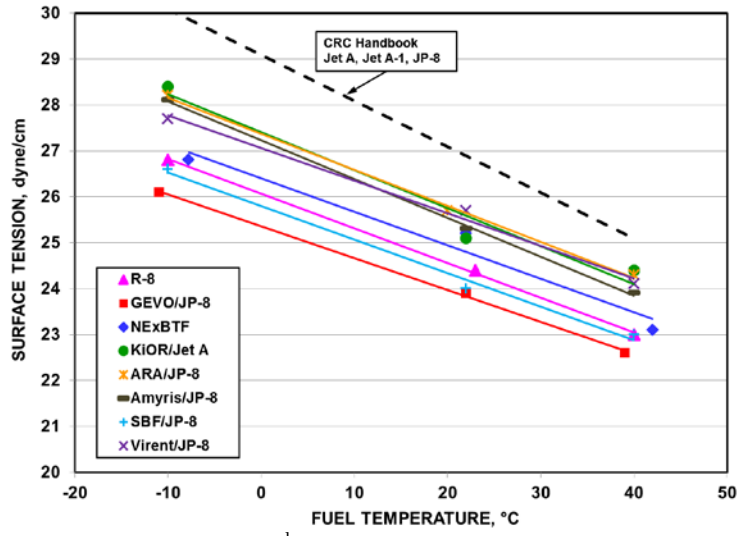


Figure 9-c. 2nd Generation Fuels and Blends

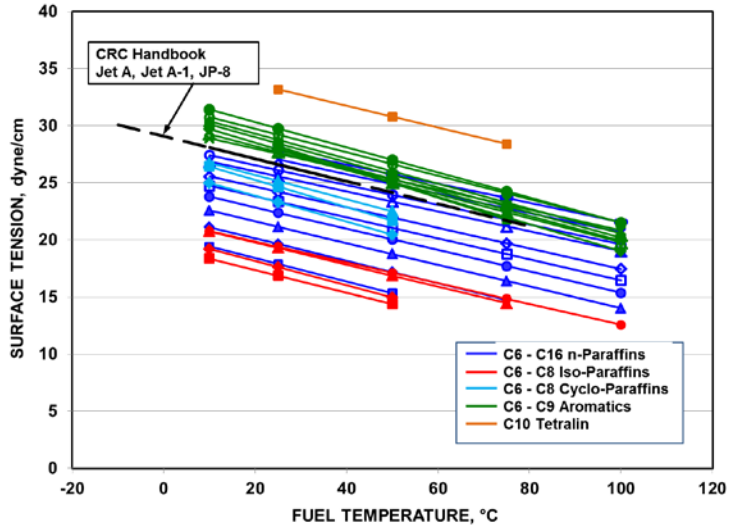


Figure 9-d. Pure Hydrocarbons

Figure 9. Surface Tension of Hydrocarbon Fuels

3.3 Other D4054 Fit-for-Purpose Bulk Properties

There are several other important bulk properties in the fit-for-purpose evaluation protocol that are primarily dependent upon or strongly correlated with density:

- Dielectric constant
- Water solubility
- Air solubility

3.3.1 Dielectric Constant vs. Temperature

Figure 10-a presents the data for dielectric constant for the CRC WFS fuels. The data for all of the fuels are linear; it appears that the slope increase slightly for the fuels with higher dielectric constant. The data from the CRC Handbook fit the data set.

Figure 10-b presents the data for the F-T and HEFA fuels. These data are also linear with temperature and essentially parallel, but they are, for the most part, lower than the WFS data of Figure 10-a and have a slightly lower slope. The two fuels that lie within the WFS boundaries are conventional jet fuels. The fuels with the lowest values are unblended SPKs, i.e., they contain no aromatics, and have very low densities that don't meet the specification minimum.

The temperature characteristics for the dielectric constant of the 2nd generation renewable fuels are presented in Figure 10-c. Like the F-T and HEFA fuels, the data are lower than the data for the WFS fuels, with two exceptions: the ARA and KiOR fuels. These fuels both contain significant levels of synthesized aromatics and have higher densities than the other blends.

The dielectric constants of pure hydrocarbons are presented in Figure 10-d. SUPERTRAPP does not provide calculations for dielectric constant. These data were calculated from equations and constants provided in the Handbook of Chemistry and Physics.[17] The fuels for which data were available was limited, and there were no data for iso-paraffins. The results are linear with temperature. While the data for the saturates are very close to the WFS data, the aromatics exhibit much higher dielectric constants; also, the slopes are higher for the aromatics.

Although the dielectric constants of the pure aromatic types are much higher than for the saturates, the dielectric constants of the complete fuels, whether or not they contain aromatics, are all very similar in value. This suggests that the dielectric constant does not blend linearly with aromatics are present. It seems probable that since the more polar aromatics are dispersed, that the saturates act as a carrier and control the value of the dielectric constant while the aromatics provide a minor increase relative to their concentration.

Regardless of the reason, the dielectric constants of the synthesized kerosenes and their blends have temperature dependencies which are very similar to conventional fuels irrespective of resource, processing, or composition. It will be shown in the next section that the reason the blends with SPKs have lower dielectric constants is that they have lower density.

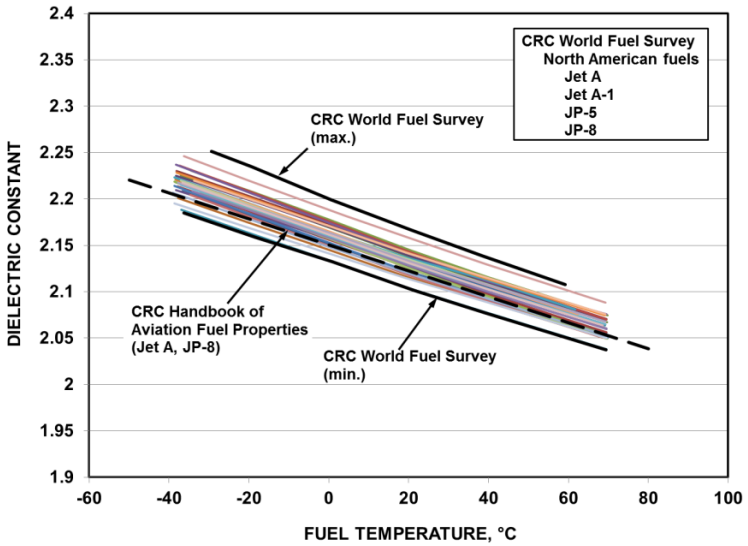


Figure 10-a. CRC World Fuel Survey

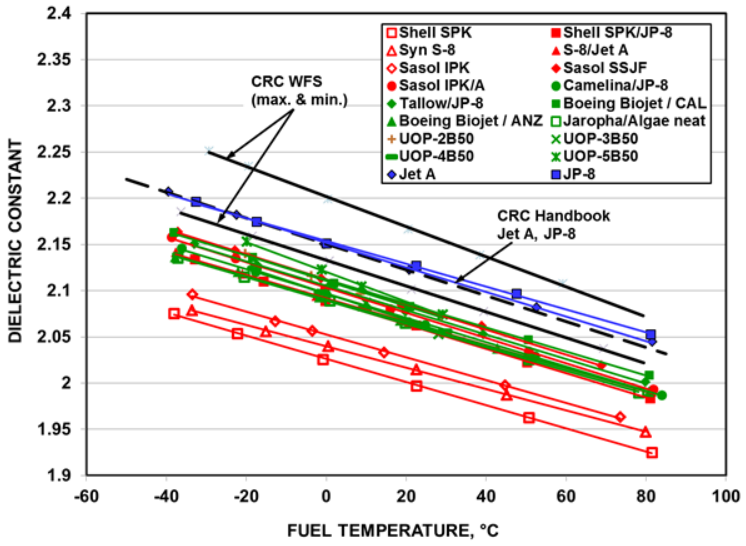


Figure 10-b. F-T and HEFA Fuels and Blends

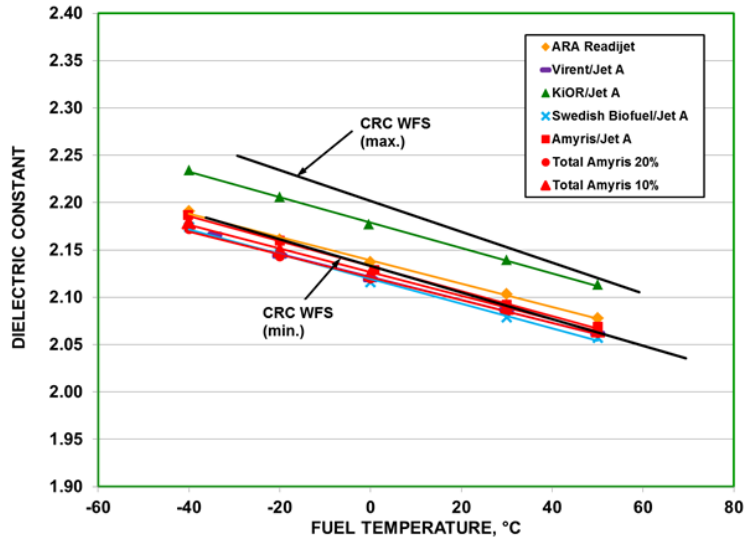


Figure 10-c. 2nd Generation Renewable Fuels and Blends

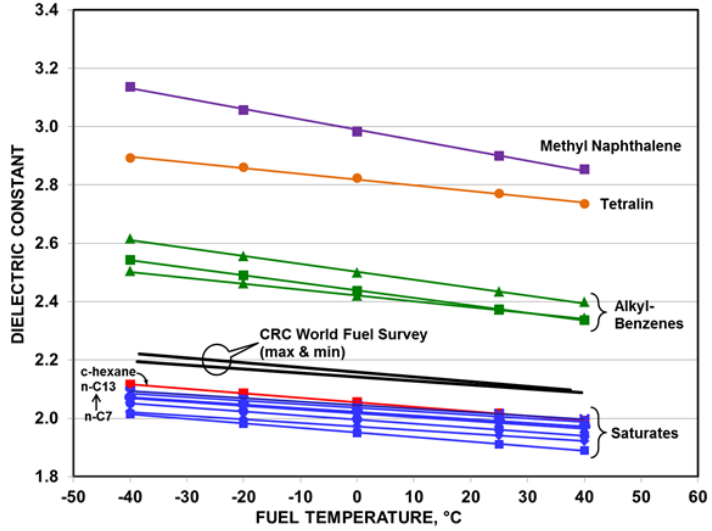


Figure 10-d. Pure C10 Hydrocarbons

Figure 10. Dielectric Constant of Hydrocarbon Fuels

3.3.2 Dielectric Constant vs. Density Correlation

The dielectric constant is used to calculate fuel density for tank gauging on-board aircraft. It is therefore worthwhile to consider the relationship between the dielectric constant and density for the synthesized fuels and blends in addition to the temperature relationship. The dielectric-density characteristics were developed using the data from Figures 1 and 10 for density and dielectric constant, respectively.

Figure 11-a presents the dielectric-density characteristics of the CRC WFS fuels. As with the other properties, the correlations are linear and essentially parallel, but there is a slight increase in slope for the fuels with higher dielectric constant. Although the CRC Handbook contains data for both dielectric vs. temperature and density vs. temperature, a valid dielectric-density data curve could not be made because the data were not necessarily for the same fuel.

Figure 11-b presents the dielectric-density characteristics of the F-T and HEFA fuels; the boundaries of the CRC WFS fuels are used as reference. As a data set, the dielectric-density characteristics of these fuels are linear with very similar slopes, although, like the WFS fuels, there is a small, but consistent, increase in slope for the fuels with higher dielectric constant. Although the values are in the same range as for the WFS fuels, the slopes of these fuels are noticeably less than for the WFS fuels.

Figure 11-c presents similar data for the other renewable fuels. Like the F-T and HEFA fuels, the data lines are linear and of similar slope. Also like the F-T and HEFA fuels, the slopes are, again, lower than for the WFS fuels.

The dielectric-density characteristics of the pure hydrocarbons present a significantly different picture as shown in Figure 11-d. The dielectric scale had to be increased because of the much wider range of values. The available data for saturates are somewhat similar to the CRC WFS fuels as indicated by the reference lines; however, the data for the different aromatic families are significantly different, being much higher in density and dielectric constant. While the slopes of the aromatic lines are not vastly different than those of the saturates or WFS fuels, they do follow the trend of increasing slope with higher dielectric constant. These data also explain why the dielectric constants are lower for fuels with lower aromatics.

A concern was raised by an airframe manufacturer a couple years ago about the fact that the slope of the dielectric-density correlation for some of the synthesized kerosenes and their blends was different than the average of the WWS fuels, and whether that would introduce an error in the fuel tank gauging system despite these fuels meeting all specification test requirements. At the time the errors for the fuels in question were found to be acceptable. However, it may be necessary to demonstrate the acceptability of the dielectric-density correlation for fuel with synthesized hydrocarbons. Based on the data for pure hydrocarbons, it may be the low aromatic content and lack of naphthalenes in the blends that cause the variation in slopes and absolute values, but this will be equally true for both conventional and synthetic blends. Therefore, it is concluded that dielectric constant vs. density characteristics are determined by relevant specification composition and physical properties and not the presence or absence of synthetic components.

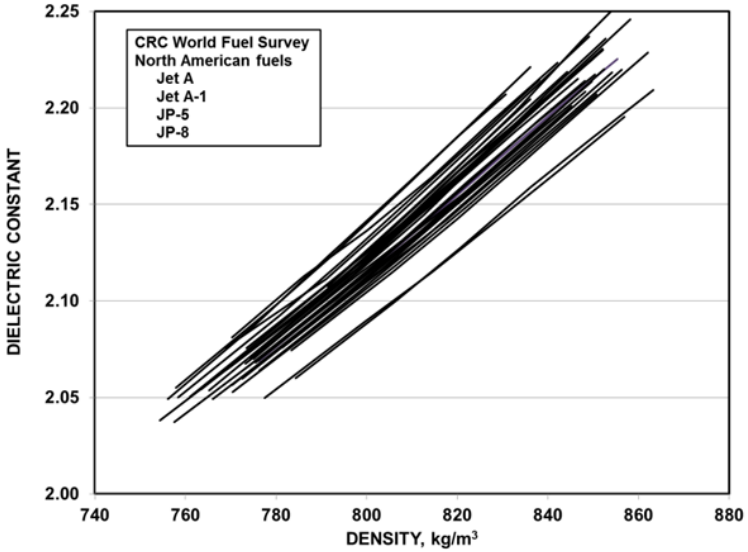


Figure 11-a. CRC World Fuel Survey

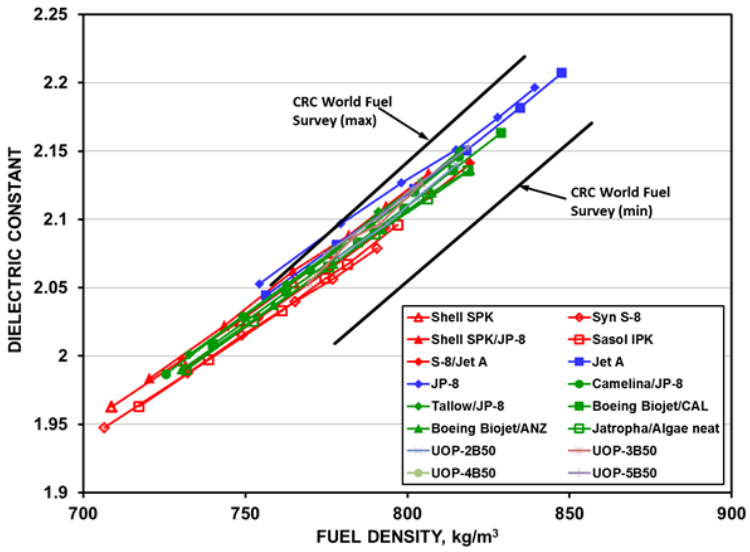


Figure 11-b. F-T and HEFA Fuels and Blends

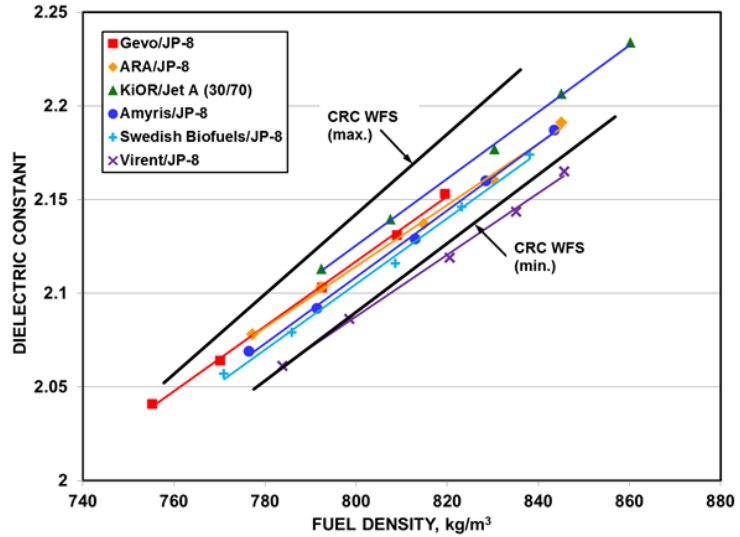


Figure 11-c. 2nd Generation Renewable Fuels and Blends

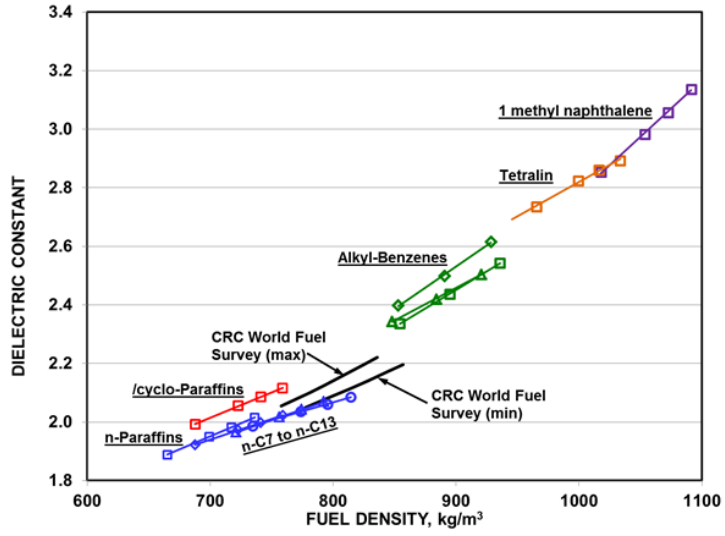


Figure 11-d. Pure C10 Hydrocarbons [17]

Figure 11. Dielectric – Density Correlation for Hydrocarbon Fuels

3.3.3 Water Solubility vs. Temperature

Water solubility is dependent on the hydrocarbon composition of the fuel, and may be affected by the use of additives such as fuel system icing inhibitors.[5] Water solubility can also be increased by the presence of non-hydrocarbon materials such as detergents, surfactants, oxygenated organics, and some additives, such as FSII. Synthesized kerosenes with breakpoints ≥ 325°C would not contain such materials except by contamination through poor storage and handling.

The CRC WFS fuels were not analyzed for water solubility; however, the European Aviation Safety Agency (EASA) conducted tests on water solubility on five jet fuels from different countries. The tests were conducted with a Metrohm Karl Fischer Coulometer (KF 831). The results, presented in Figure 12-a, are exponential with temperature as are the data from the CRC Handbook. The results show that water solubility increases with aromatic content. The change in aromatic content does not alter the parallel nature of the data lines.

Water solubility was not evaluated for the F-T fuels. The first fuels to be evaluated were the HEFA fuels; these results are shown in Figure12-b. As with the EASA data, water is more soluble in the fuels that contain aromatics, i.e., the blends. These data lines are also parallel, but they appear more linear with temperature rather than exponential as expected. The blends have greater water solubility than the pure HEFA which is consistent with having a greater aromatic content.

The water solubility of the other renewables and the fully synthetic Sasol IPK/A, which contains synthesized aromatics, are shown in Figure 12-c. The data for these fuels are exponential, but do not appear to be parallel. The KiOR fuel had some issues with marginal thermal stability so it may have contained some non-hydrocarbons that may have been responsible for the relatively high water solubility.

From these results, it is seen that hydrocarbon kerosenes with low aromatic content will have lower water solubility. At the upper end of the spectrum, since there is a maximum limit on aromatics, it is not expected that water solubility would be any greater in synthesized kerosenes than for conventional fuels.

Thus, the question of water solubility and separation is really a question of contamination with non-hydrocarbon contaminants such as detergents or surfactants. These have been controlled in the processing of synthesized kerosenes by the requirement for a thermal stability breakpoint ≥ 325°C. (Recall that the KiOR fuel in Figure 12-c did not meet this requirement.) If this requirement is maintained, water solubility will be a question of cleanliness in storage and handling just like it is with conventional fuels.

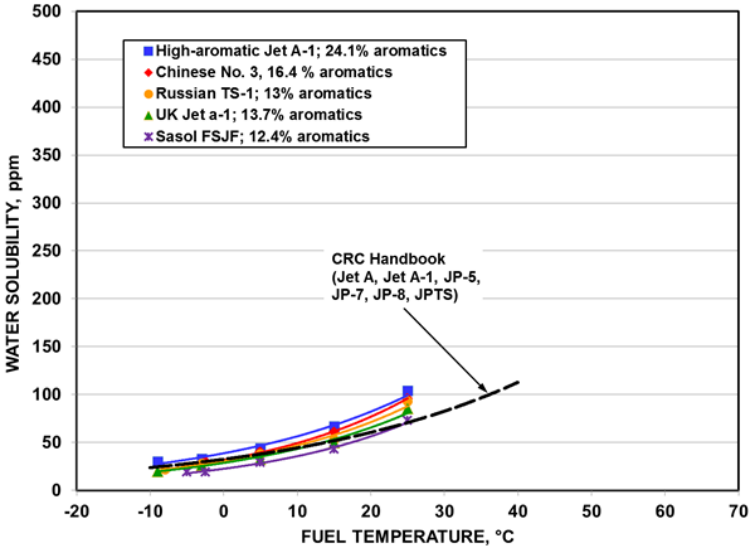


Figure 12-a. EASA Report [6]

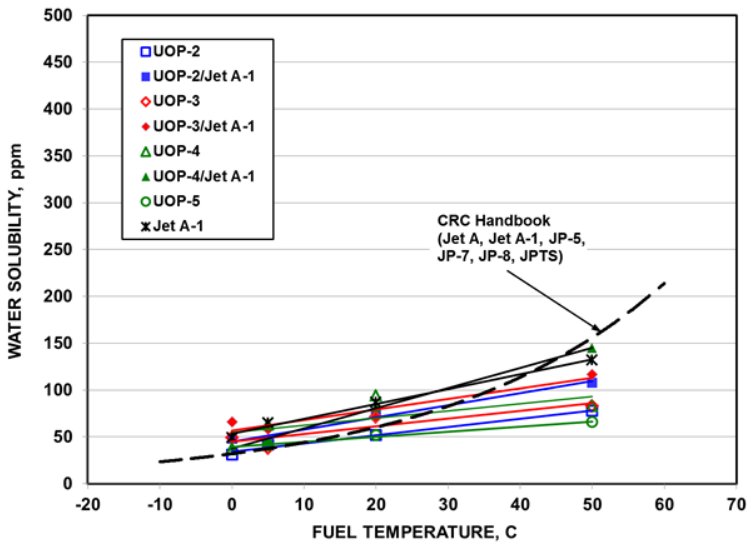


Figure 12-b. HEFA Fuels and Blends

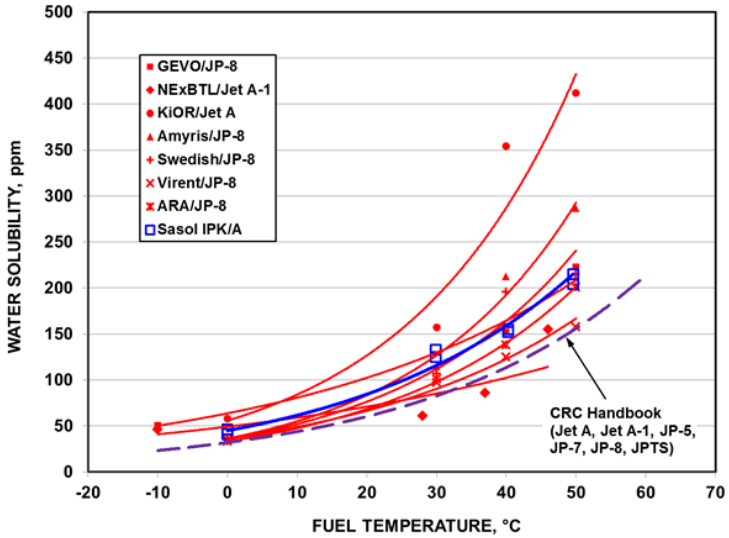


Figure 12-c. 2nd Generation Fuels and Blends

A data base on the solubility of water in pure hydrocarbons was not found.

Figure 12-d. Pure Hydrocarbons

Figure 12. Water Solubility in Hydrocarbon Fuels

3.3.4 Air Solubility

Air solubility is not a part of the ASTM D4054 fit-for-purpose evaluation protocol; however, it is important in the operation of fuel systems. Air solubility was not determined for the CRC WFS fuels or the F-T fuels, but data on air/nitrogen/oxygen solubility was included in the technical reports for the HEFA and 2nd-generation renewable fuels. Air is 99.0%(v) nitrogen plus oxygen with argon comprising another 0.9%(v). At low and moderate temperatures, the solubility of all three of these gases in liquid hydrocarbons decreases with increasing density. (Note that at fuel temperatures above around 80 to 100°C, a factor involving the vapor pressure of the fuel becomes dominant and fuels with higher density can have lower solubility as expressed by the Bunsen coefficient.) Figure 13 presents solubility data for nitrogen, oxygen, argon, and air in various synthesized kerosenes, conventional jet fuels, and blends with an air ullage. The concentrations were measured by GC/MS in selected ion monitoring mode (SIM). These data show strong linear correlations with density independent of source, processing, or composition.

Since there are limits on both the maximum and minimum density of Jet A/Jet A-1/JP-8, it stands to reason that all fuels containing synthesized hydrocarbons, whether as blends or in fully synthetic fuels, will have air solubility that is typical of conventional fuels.

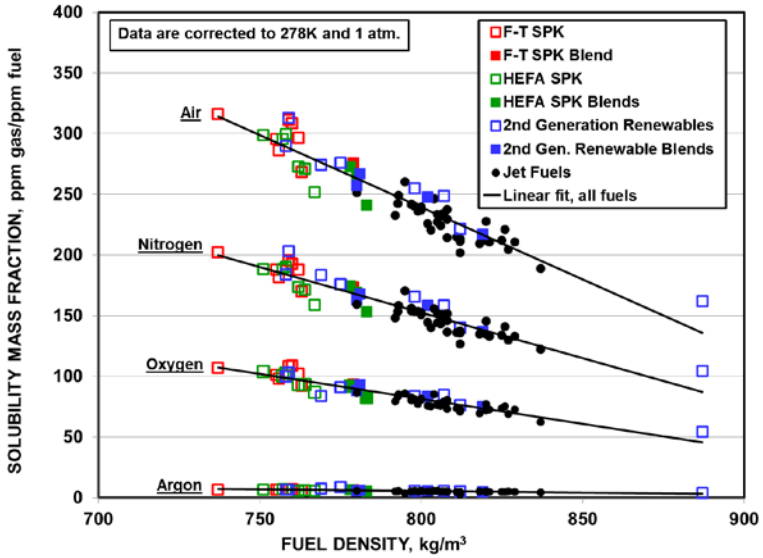


Figure 13. Solubility of N_2, O_2, and Argon in Hydrocarbon Fuels (with Air Ullage) [19]

4.0 RESULTS AND DISCUSSION

4.1 Fuel Chemistry and Bulk Physical Properties

It is obvious from the comparisons of each property that the temperature dependencies of each property were the same for synthesized kerosenes and their blends with conventional jet fuels as they were for conventional jet fuels. Moreover, if the synthesized fuels and blends met the minimum density requirement, then all of the property values of the synthesized kerosenes and blends were also typical of conventional jet fuels. The fact that the temperature dependencies were linear, with the slight exception of isentropic bulk modulus, and parallel, means that that this observation is true regardless of composition.

For most of the properties, composition, mostly aromatic content, does affect the value at a given temperature, but does not affect the slope. As an example, for a given temperature, the densities of cyclo-paraffins are slightly higher than the densities of normal and iso-paraffins, which have similar densities; in comparison, the densities of double-ring cycloparaffins and single-ring aromatics are significantly higher. The densities of cyclo-aromatics, e.g., tetralins, and double-ring aromatics are higher yet. However, when blended together, with an aromatic content between 8 and 25%(vol), the densities, as well as all the other properties, are all typical of conventional jet fuel. This is only possible because the temperature dependencies of each property are linear and parallel, regardless of hydrocarbon family or carbon number. If the temperature dependencies were not linear and parallel, the temperature dependencies of the final fuels would not be linear and parallel, but would depend upon the composition.

Since these results were shown to be true for pure hydrocarbons as well as kerosene fuels, the results can be generalized to all hydrocarbon kerosenes that are mixtures of many hydrocarbon molecules distributed over many carbon numbers. The presence of aromatics, whether natural or synthesized, does not affect the temperature dependence, only the value.

With that in mind, it is worthwhile to document the chemistry of the fuels in the CRC World Fuel Survey that were the basis of the physical properties reported here. Chemical analyses of the fuels by two-dimensional gas chromatography, or GCxGC, have been conducted by the University of Dayton Research Institute (UDRI). Table 2 provides a global summary of the hydrocarbon composition of the fuels. Detailed analyses are provided in Appendix A2-1 through A2-4.

Thus, if a synthesized kerosene and/or its blend with conventional jet fuel has chemistry that roughly falls with the guidelines of Table 2 and meets the specification limits boiling point distribution, and flash point, the chemistry and bulk physical properties have to be typical of conventional jet fuel, regardless of resource or process.

Table 2. Hydrocarbon Composition of the Fuels in the CRC World Fuel Survey

Hydrocarbon Family	Composition, %(m)
Paraffins (n + iso)	22 to 72
- Normal paraffins	- 6 to 30
- Iso-paraffins	- 15 to 56
Cyclo-paraffins (total)	15 to 64
- Monocyclic	- 11 to 44
- Dicyclic	- 3 to 20
- Tricyclic	- 0 to 0.4
Aromatics (total)	13 to 26
- 1-ring	- 9 to 19
- Tetralins + indans	- 2 to 10
- Naphthalenes	- 0.1 to 5

This discussion suggests that many of the real concerns about a synthesized kerosene or blend as to being "fit-for-purpose" lie with the possible presence of organic and inorganic contaminants, e.g., oxygenates, sulfur, nitrogen, halogens, and metals. These are all controlled by the two specification property tables in the Annexes of D7566. Table AX.1 controls the distillation and volatility of the synthesized kerosene as well as freezing point and contaminants of gum and FAME, and requires an anti-oxidant for storage stability. Most importantly, Table AX.1 requires a JFTOT temperature of 325°C; this requirement of thermal stability was instituted to ensure that there is enough downstream hydrotreating to remove all reactive species and other organic contaminants from the fuel. This includes acids and other oxygenated organics that could attack metals and non-metallic materials, as well as detergents/surfactants that could affect water separation and filtration.

Table AX.2 further ensures the synthesized kerosene is at least 99.5% hydrocarbons and limits the most common contaminants of water, nitrogen, sulfur, halogens, and metals.

4.2 Other Characteristics: Ground Handling, Safety, and Compatibility

The above discussion does not address the elements of the D4054 Fit-For-Purpose property evaluations under the headings of "Ground Handling and Safety" and "Compatibility". It is considered very likely that further evaluation would either indicate that for hydrocarbon kerosenes with 325°C breakpoints, as described above, these elements would also have to be typical of conventional jet fuels, or would identify a few critical elements that could be added to the property table of the relevant Annex(es). For example:

- The potential issues of filtration and water separation are related to non-hydrocarbon contaminants that are removed by the requirement for the 325°C breakpoint temperature.
- The potential issues of Storage Stability, i.e., peroxides and gums, are already addressed in the Annexes by the requirement for antioxidant.
- Since the flammability characteristics are dependent only on volatility and chemistry, the flammability characteristics of any final fuel containing 8 to 25%(vol) aromatics, whether a blend or fully synthetic, will be typical of conventional jet fuel.

- Since we are dealing only with synthesized hydrocarbons in the kerosene boiling range, the synthesized fuels are fully compatible with conventional jet fuels.
- Although all of the fuel additives have been shown to be soluble and effective even in the paraffinic kerosenes, i.e., no aromatics, any concerns of solubility are alleviated by the requirement for a minimum of 8%(vol) aromatics in the final fuel, whether a blend or fully synthetic jet fuel.
- Issues with metals, both hot-section and fuel system, are related to the presence of metals and acids in the fuel, both of which are controlled in the Annex(es).
- There are two major issues with fuel compatibility of non-metallic materials, i.e., elastomers and seals: the presence of non-hydrocarbon solvents and adequate aromatics for seal swell. Both of these issues are adequately controlled by the restrictions to a hydrocarbon kerosene with a 325°C breakpoint temperature and 8 to 25%(vol) aromatics.

4.3 Opportunities

It seems perfectly feasible that these issues would be adequately controlled by the Annex(es) for synthesized hydrocarbon kerosenes with the requirements of a 325°C breakpoint and 8 – 25%(vol) aromatics in the final fuel, whether blended or fully synthetic. However, definitive technical support for these issues was not within the scope of this report. It should be recalled that of the approximately 40 synthesized kerosenes and blends that that have been evaluated to date by the industry, not one has failed to meet the requirements of the ASTM D4054 fit-for-purpose evaluation.

Recalling that Annex 1 of D7566 provided the first generic approval of synthesized paraffinic kerosenes from F-T processes because it was demonstrated that all F-T kerosenes had similar properties [7], it is felt that the data presented here lay the ground work for consideration that all synthesized hydrocarbon kerosenes with a 325°C breakpoint and 8 – 25%(vol) aromatics in the final fuel, whether blended or fully synthetic, be combined into appropriate generic Annex(es) without regard to resource or processing. Synthesized kerosenes with typical hydrocarbon composition and carbon number distribution, as demonstrated by GCxGC analysis, along with these restrictions, would then not have to go through the formal D4054 fit-for-purpose evaluations in the same way that FT SPKs and HEFA SPKs are now accepted under Annexes 1 and 2, respectively without further testing. One possible scenario of Annexes is as follows:

1. Synthesized Paraffinic Kerosenes (SPK) as a blend stream for semi-synthetic jet fuel
2. Synthesized Kerosenes with Aromatics (SKA) as a blend stream for semi-synthetic jet fuel
3. Synthesized Kerosenes with Aromatics (SKA) as fully synthetic jet fuels

4.4 Summary of Bulk Physical Properties

The temperature dependencies of the bulk physical properties examined in this report are easy to summarize – they are all the same:

1. With one minor exception, all of the thermodynamic and transport properties were linear with temperature for all of the conventional and synthesized fuels and blends thereof. The one exception was for isentropic bulk modulus which had a slight curvature because it is a function of the square of the speed of sound.

2. For each property, the temperature dependencies of all the fuels, regardless of resource or processing, were essentially parallel; variations in slope were small and considered insignificant.
3. The presence of aromatics did not change the temperature dependence of any of the properties, whether synthesized or natural.
4. The above observations about the complete fuels were confirmed by the data for pure hydrocarbons. All of the properties exhibited linear temperature dependence and had virtually the same slope regardless of carbon number or hydrocarbon family.
5. If the synthesized fuel or blend contained at least 8%(vol) aromatics, then the actual values of the properties were typical of conventional fuels and the minimum density specification was met.
6. Therefore, fuels meeting all standard specification requirements for conventional and/or specific controls on synthetic blends will have physical fit-for-purpose properties that are within experience with respect to absolute values, temperature dependency, and relationship to specification requirements that impact on those FFP property values. In other words, a synthetic blend of given specification properties will behave the same as a conventional fuel with equivalent specification properties.

5.0 CONCLUSIONS

Hydrocarbons don't know where they came from. The bulk physical properties of all hydrocarbon kerosenes, whether synthesized or natural, have the same temperature dependency regardless of resource or processing. Moreover, if the aromatic content is between 8 and 25%(vol), and the specification requirements for density, viscosity, flash point, and freezing point are met, the synthesized kerosenes and/or their blends with conventional jet fuels will have bulk physical properties that are typical of conventional jet fuels, both in value and temperature dependence.

The most significant effect that aromatics have on bulk physical properties is to increase density; the effects on other properties, such as specific heat, sound speed, bulk modulus, and air solubility, are related to density effects. Most importantly, aromatics do not change the temperature dependencies of bulk properties. While aromatics do have significantly different dielectric properties, the effect on a blended fuel appears to be rather minor.

Thus, from the standpoint of physical properties, there should be no concerns on use of synthesized aromatics if they are distributed with no dominant isomers and concentrations between 8 and 25% in the final fuel. (Note, there may also be limitations required for the presence of cyclo-aromatics, i.e., tetralins and indans, and naphthalenes. Also, there are known effects on elastomeric materials. These issues were not a part of this evaluation.)

6.0 RECOMMENDATIONS

It is recommended that further technical evaluations be made on the fit-for-purpose properties and characteristics not evaluated in this report to determine if synthesized hydrocarbon kerosenes with JFTOT breakpoint temperatures ≥ 325°C can be safely incorporated into generic D7566 Annexes without regard to resource or process.

7.0 REFERENCES

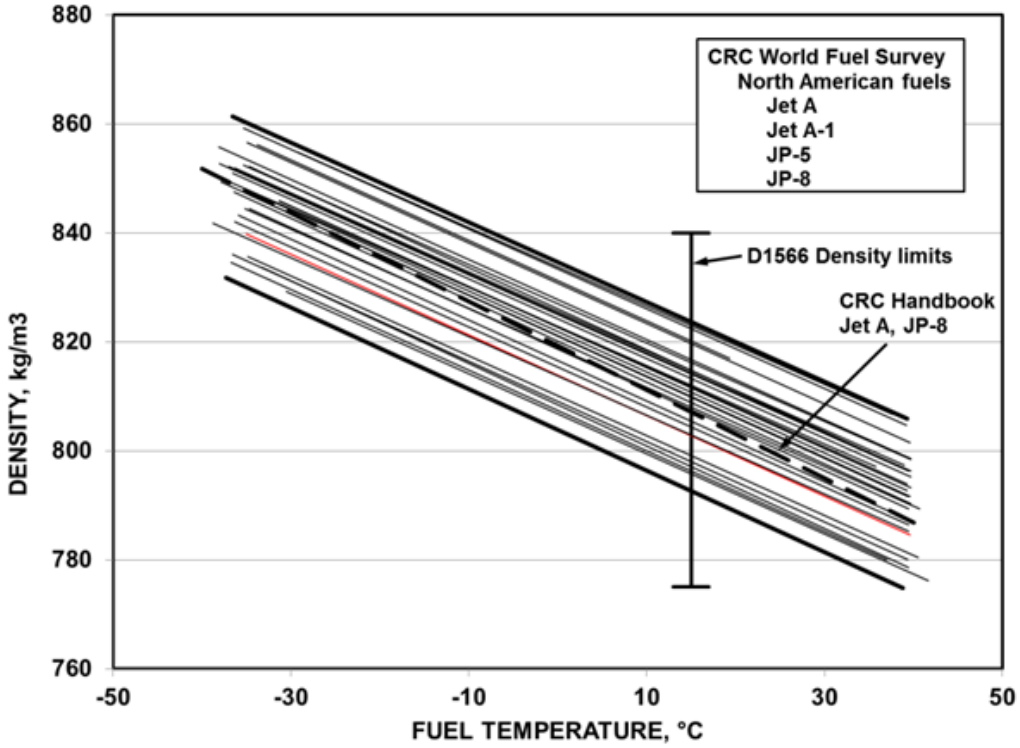
1. Defence Standard 91-91 Issue 7, Turbine Fuel, Aviation Kerosene Type, Jet A-1 NATO Code: F-35 Joint Service Designation: AVTUR, February 2011. Available at www.dstan.mod.uk.
2. D4054 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives", ASTM International, West Conshohocken, PA, 2010. Available at www.astm.org.
3. ASTM D7566, "Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," ASTM International, West Conshohocken, PA, 2010. Available at www.astm.org.
4. Hadaller, O.J. and Johnson, J.M., "World Fuel Sampling Program," CRC Report No. 647, Coordinating Research Council, Alpharetta, GA, June 2006. Available at www.crcao.org.
5. Handbook of Aviation Fuel Properties, CRC Report No. 668, 4th Edition, Coordinating Research Council, Alpharetta, GA, 2014. Available at www.crcao.org.
6. Lam, Joseph K.-W., et al, "WAFCOLT – Water in Aviation Fuel Under Cold Temperature Conditions", Airbus Report RP1140098 issue 2 to European Aviation Safety Agency (EASA), 2010.
7. Moses, Clifford A., "Comparative Evaluation of Semi-Synthetic Jet Fuels," Final Report, CRC Project AV-2-04a, Coordinating Research Council, Alpharetta, GA, September 2008. Available at www.crcao.org.
8. Bessee, Gary B, Hutzler, Scott A, and Wilson, George R, "Analysis of Synthetic Aviation Fuels", AFRL-RZ-WP-TR-2011-2084, April 2011.
9. Hutzler, Scott, "Gap Evaluations of Fischer-Tropsch (FT) Fuels", final report for SwRI Project No. 08-13549, March 2009.
10. Moses, C.A., Wilson, G.R., and Roets, P.K.R., "Evaluation of Sasol Synthetic Kerosene for Suitability as Jet Fuel", SwRI Report No. 08-04438, December 2003.
11. Moses, Clifford A., "Evaluation of Synthesized Aromatics Co-Produced with Iso-Paraffinic Kerosene for the Production of Semi-Synthetic Jet Fuel", Technical Report CAM-TR-2015-1, April 2015.
12. Moses, Clifford A., "Evaluation of F-T Kerosenes Containing Synthesized Aromatics as Blending Streams to Make Semi-Synthetic Jet Fuel", Technical Report CAM-TR-2013-1, March 2013.
13. Evaluations of Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPKs), ASTM Report D02-1739 v5.0, May 2010.
14. Hutzler, Scott A. et al, "Fit-for-Purpose (FFP) and Dynamic Seal Testing of Alternative Aviation Fuels", Air Force Report No. AFRL-RZ-WP-2014-0226, August 2014.
15. "NIST Thermophysical Properties of Hydrocarbon Mixtures Database (SUPERTRAPP)", National Institute of Standards and Technology, Gaithersburg, MD, August 2010.
16. "Surface Tension of Common Liquids", in CRC Handbook of Chemistry and Physics, Internet Version 2005, David R. Lide, ed., <http://www.hbcpnetbase.com>, CRC Press, Boca Raton, FL, 2005.
17. "Permittivity (Dielectric Constant) of Liquids:, in CRC Handbook of Chemistry and Physics, Internet Version 2006, David R. Lide, ed., <http://www.hbcpnetbase.com>, Taylor and Francis, Boca Raton, FL, 2006.
18. ASTM D341 Standard Practice for Viscosity-Temperature Charts for Liquid Petroleum Products

19. West, Zachary, “Dissolved Gases in Various Jet Fuels”, Technical Memorandum to Dr. Tim Edwards, University of Dayton Research Institute, 26 November 2012.

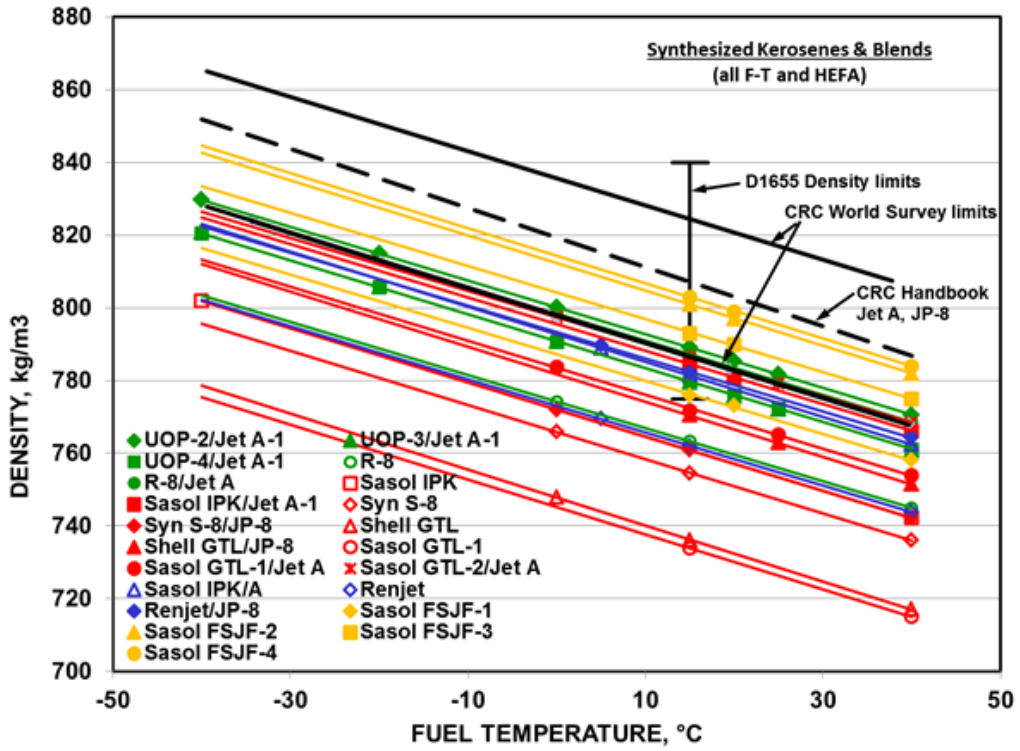
APPENDIX A

Figures A1-1 to A1-13: Larger Versions on Fuel Properties

APPENDIX A2-1 to A2-4: Hydrocarbon Composition of Fuels in the CRC World Fuel Survey

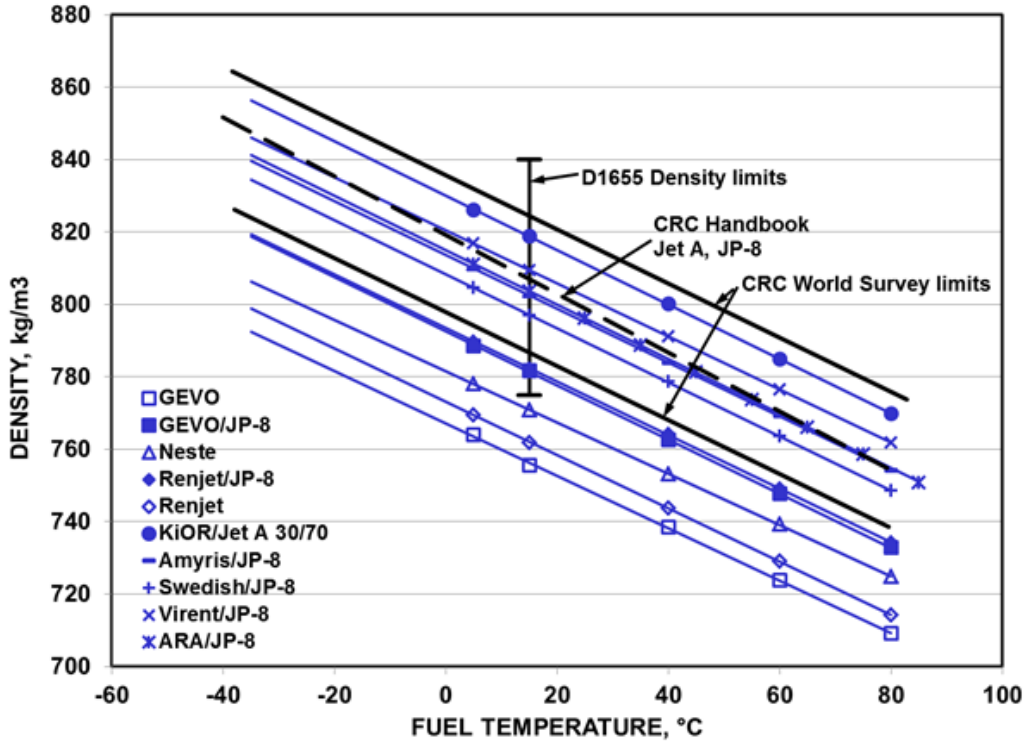


A1-1a. CRC World Fuel Survey

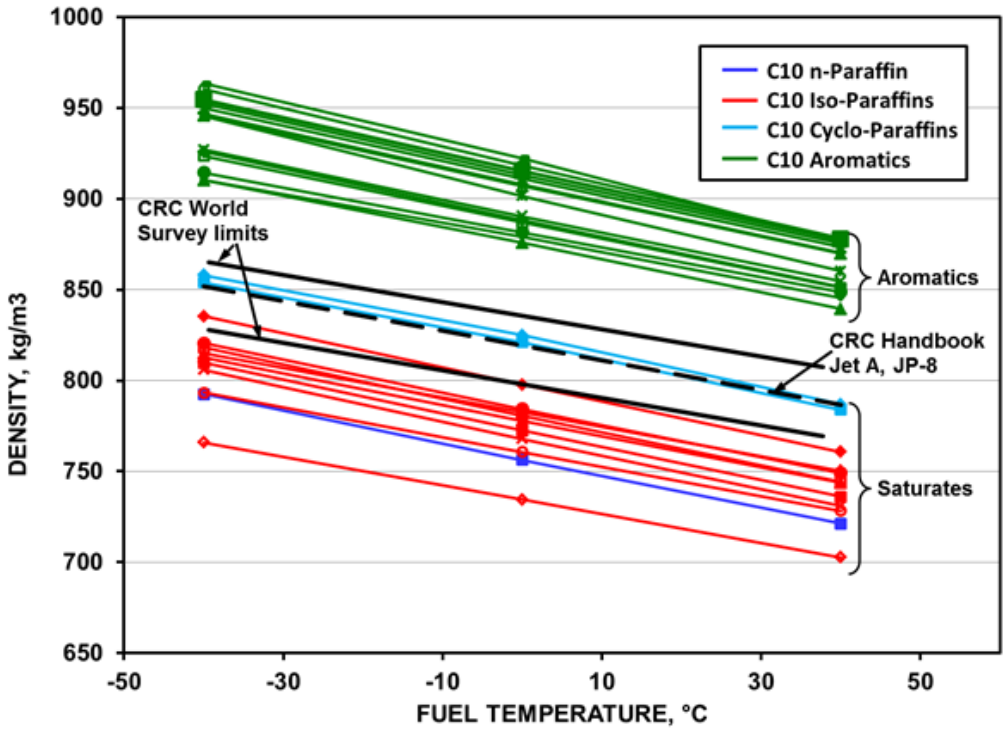


A1-1b. F-T and HEFA SPKs and Blends

Figure A1-1. Density of Hydrocarbon Fuels

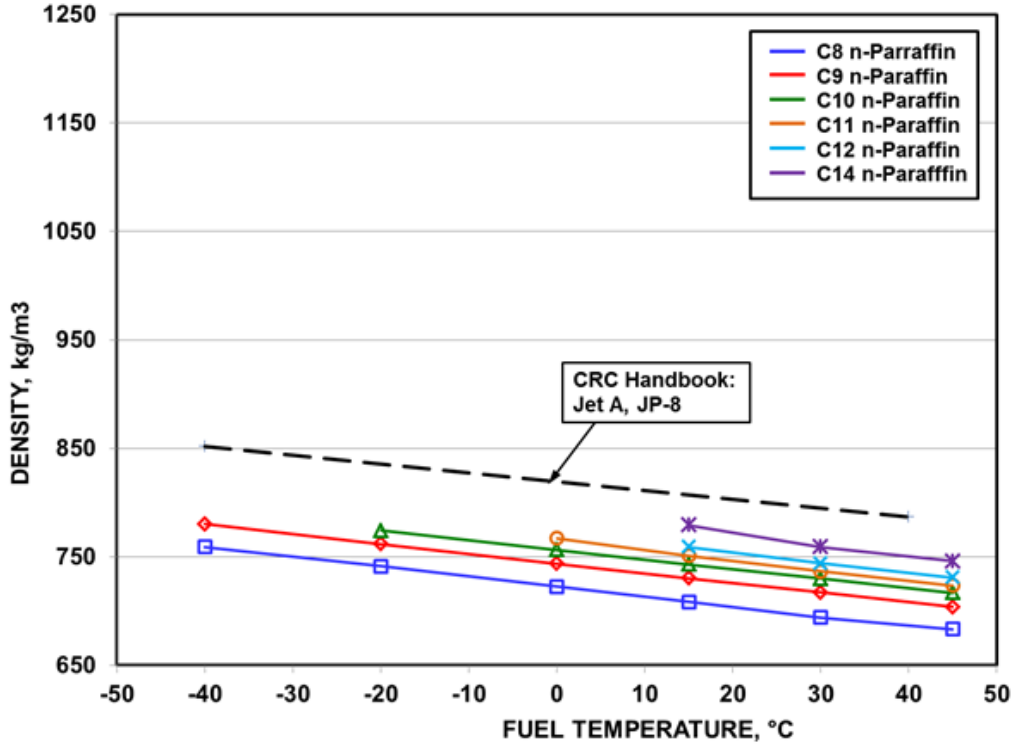


A1-1c. 2nd Generation Renewables and Blends

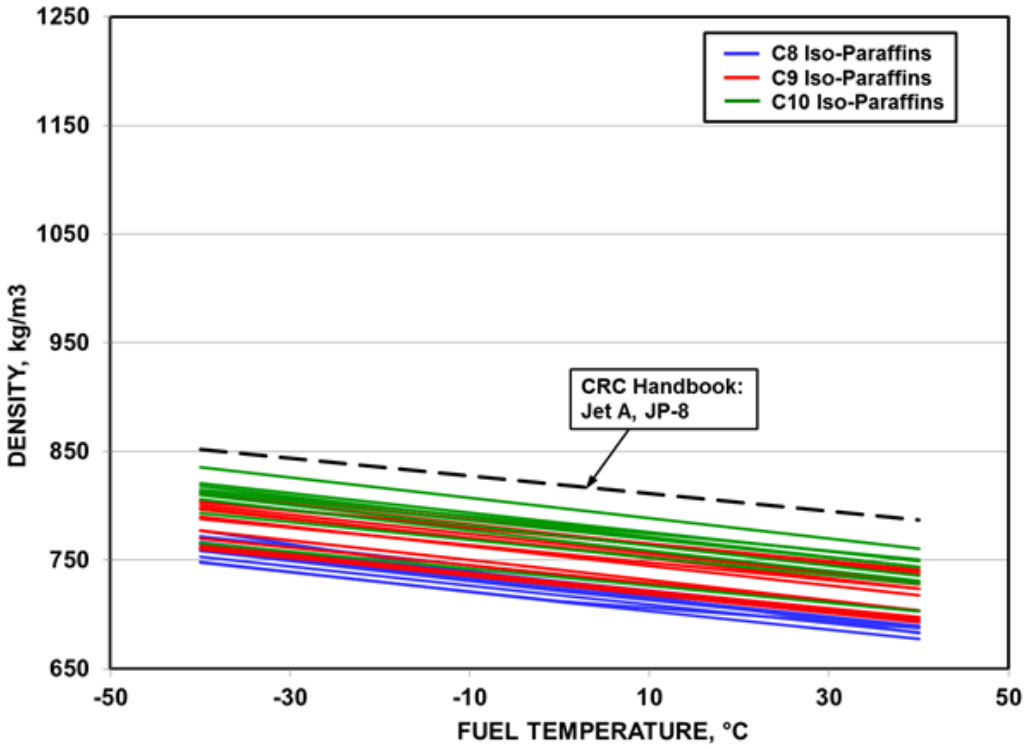


A1-1d. Pure C10 Hydrocarbons

Figure A1-1. Density of Hydrocarbon Fuels (continued)

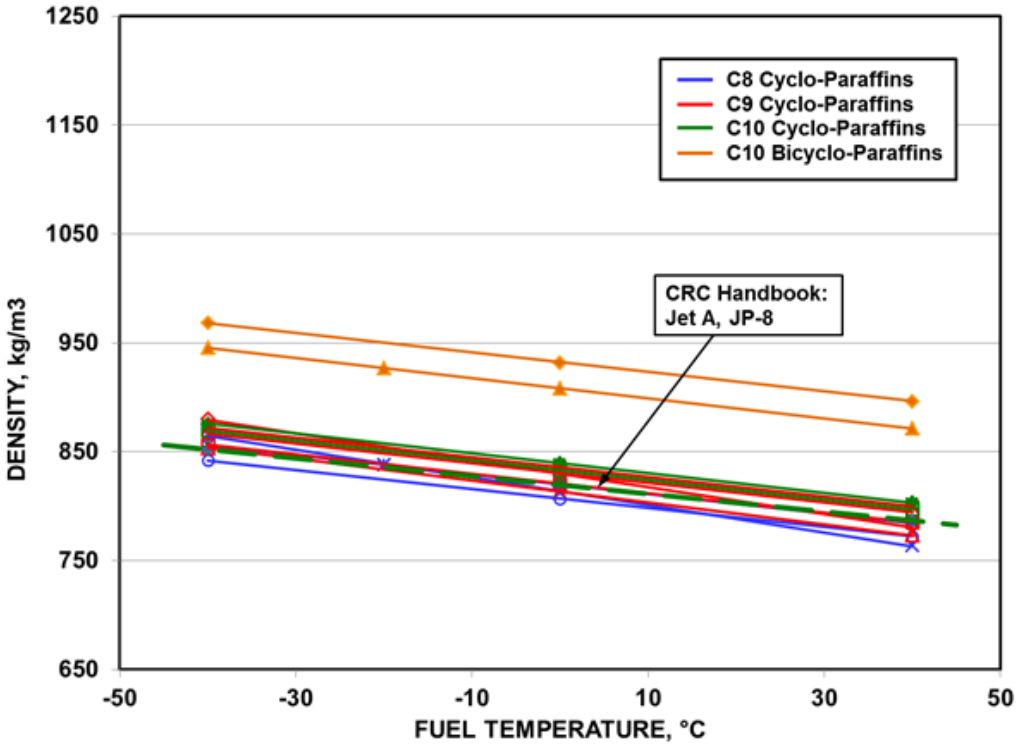


A1-2a. Density of N-Paraffins

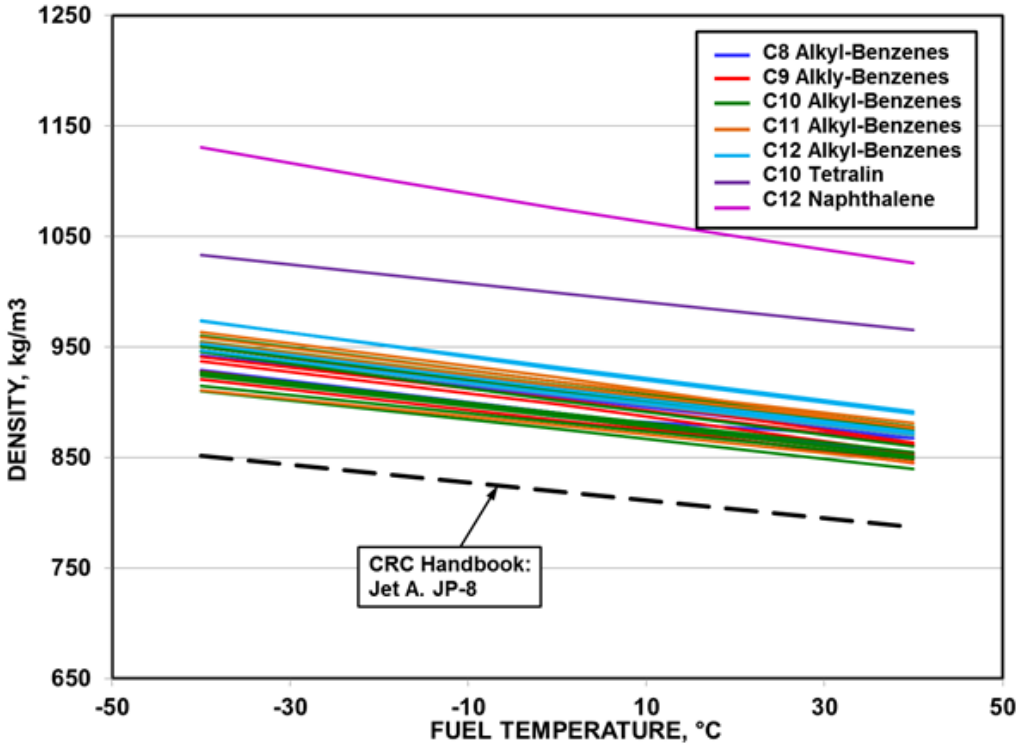


A1-2b. Density of Iso-Paraffins

Figure A1-2. Density of Pure Hydrocarbons

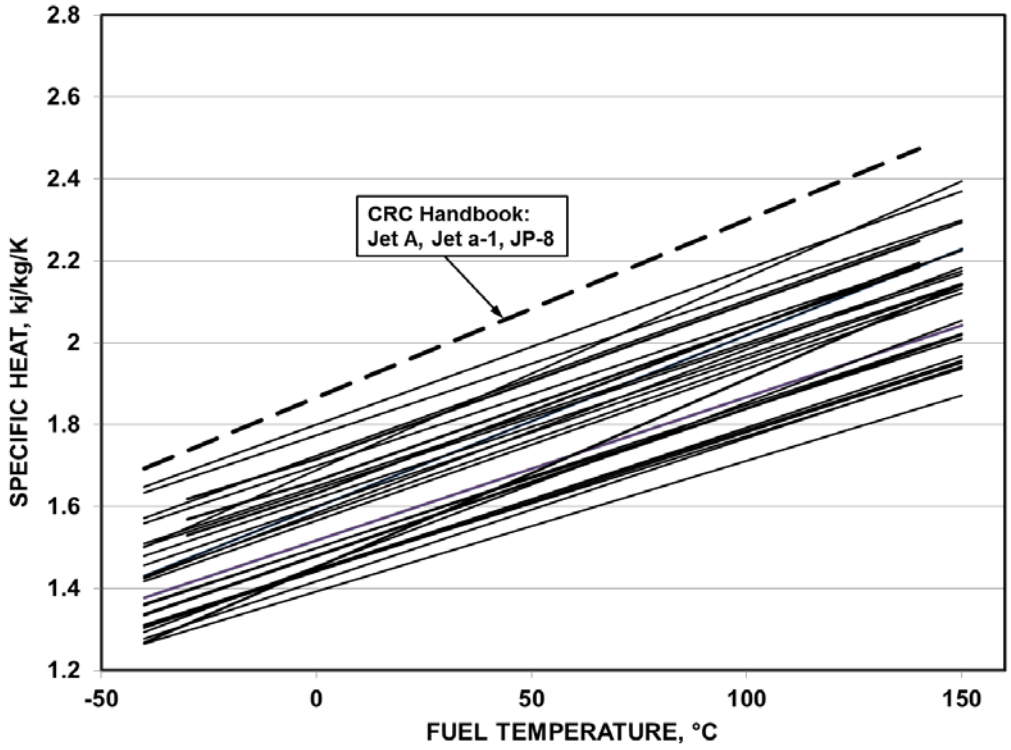


A1-2c. Density of Cyclo-Paraffins

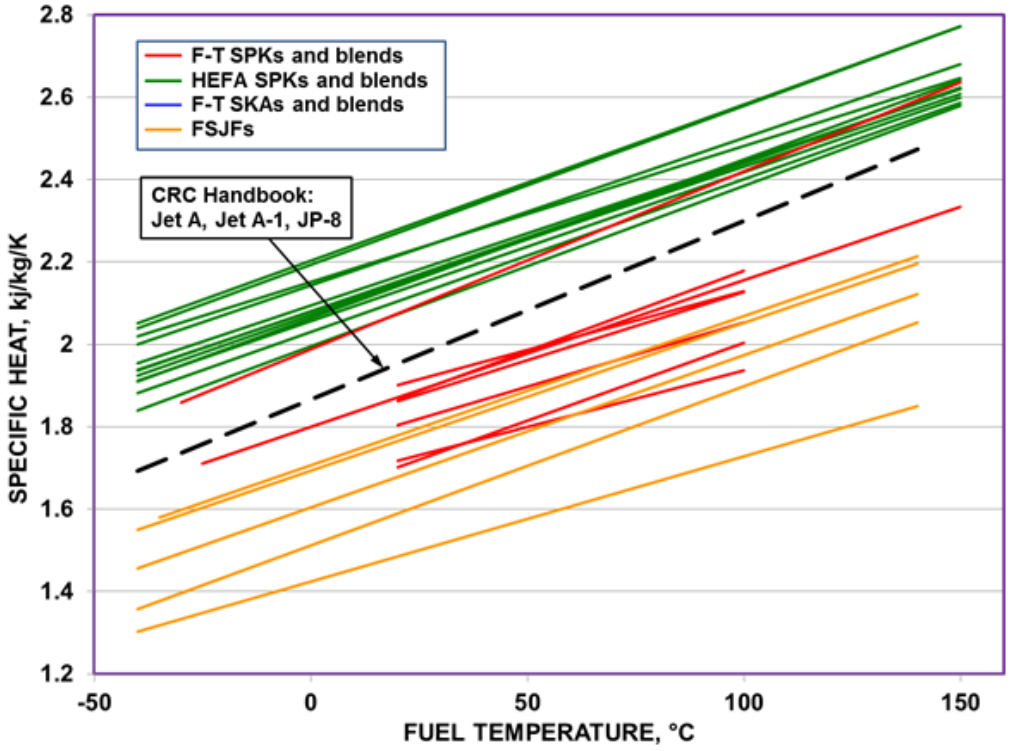


A1-2d. Density of Aromatics

Figure A1-2. Density of Pure Hydrocarbons (continued)

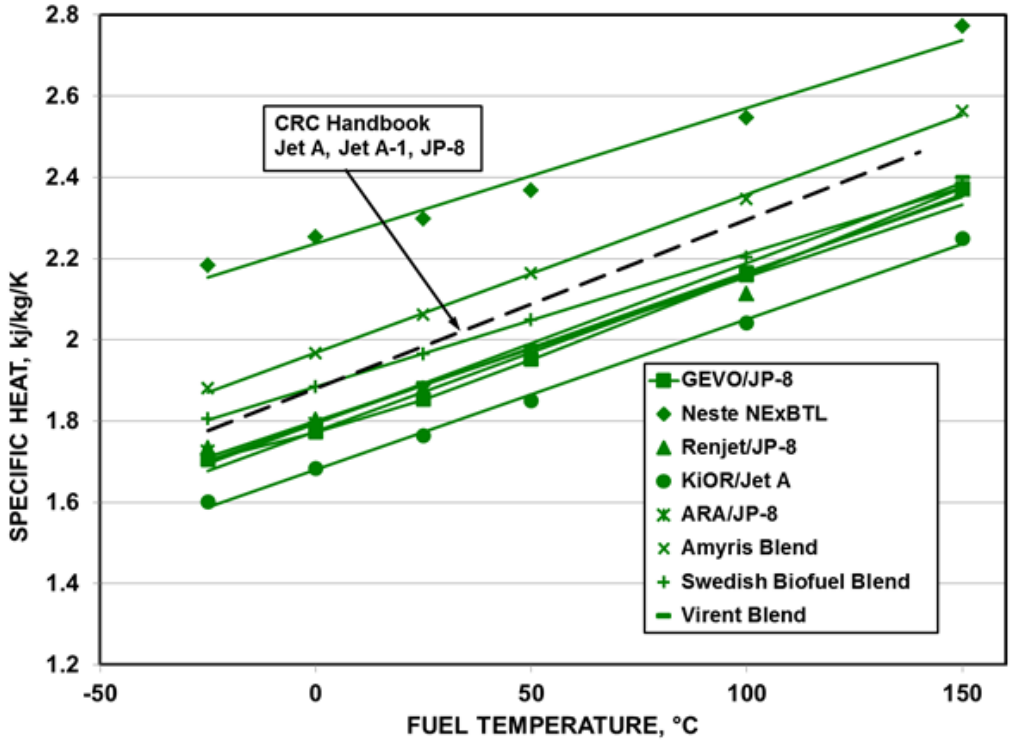


A1-3a. CRC World Fuel Survey

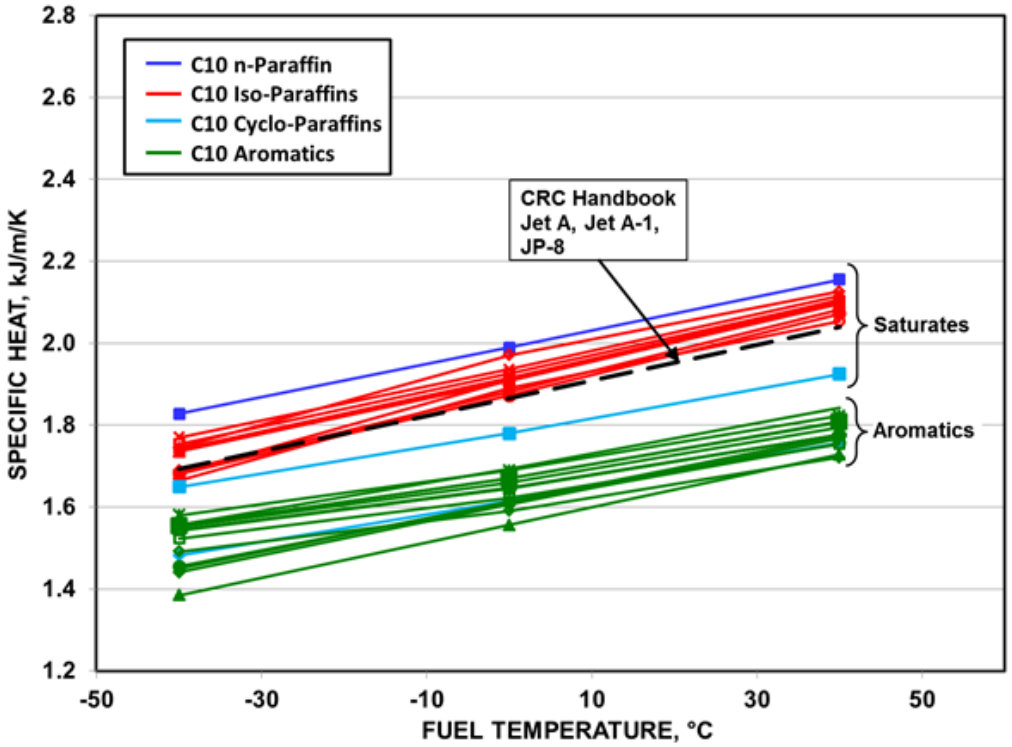


A1-3b. F-T and HEFA Fuels and Blends

Figure A1-3. Specific Heat of Hydrocarbon Fuels

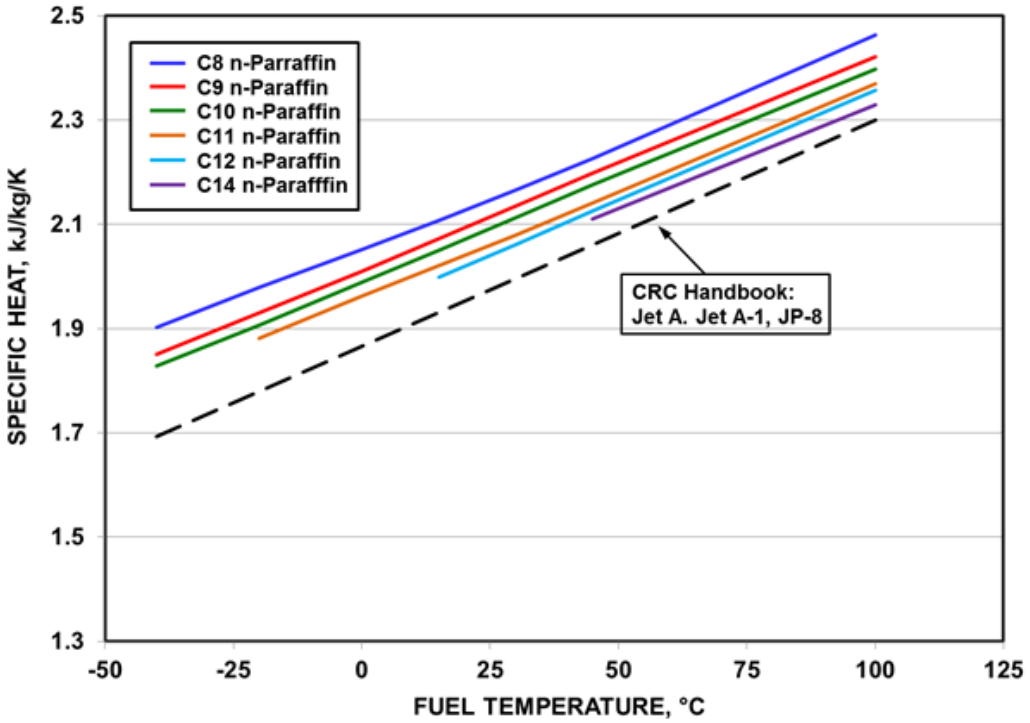


A1-3c. 2nd Generation Renewable Fuels and Blends

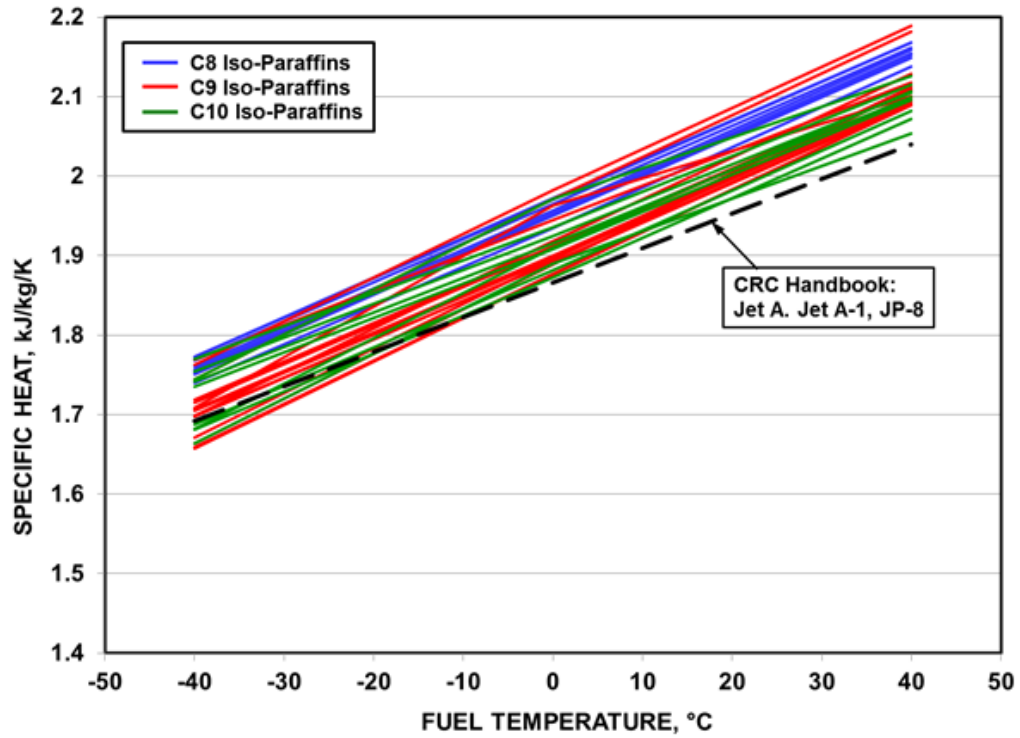


A1-3d. C10 Pure Hydrocarbons

Figure A1-3. Specific Heat of Hydrocarbon Fuels (continued)

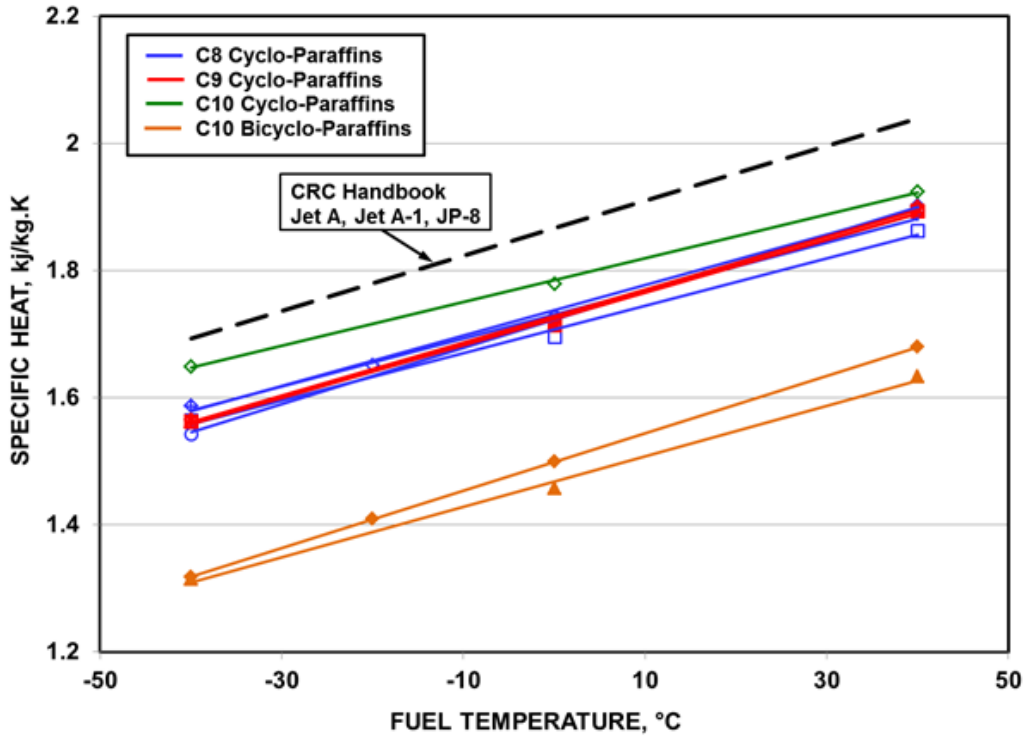


A1-4a. N-Paraffins

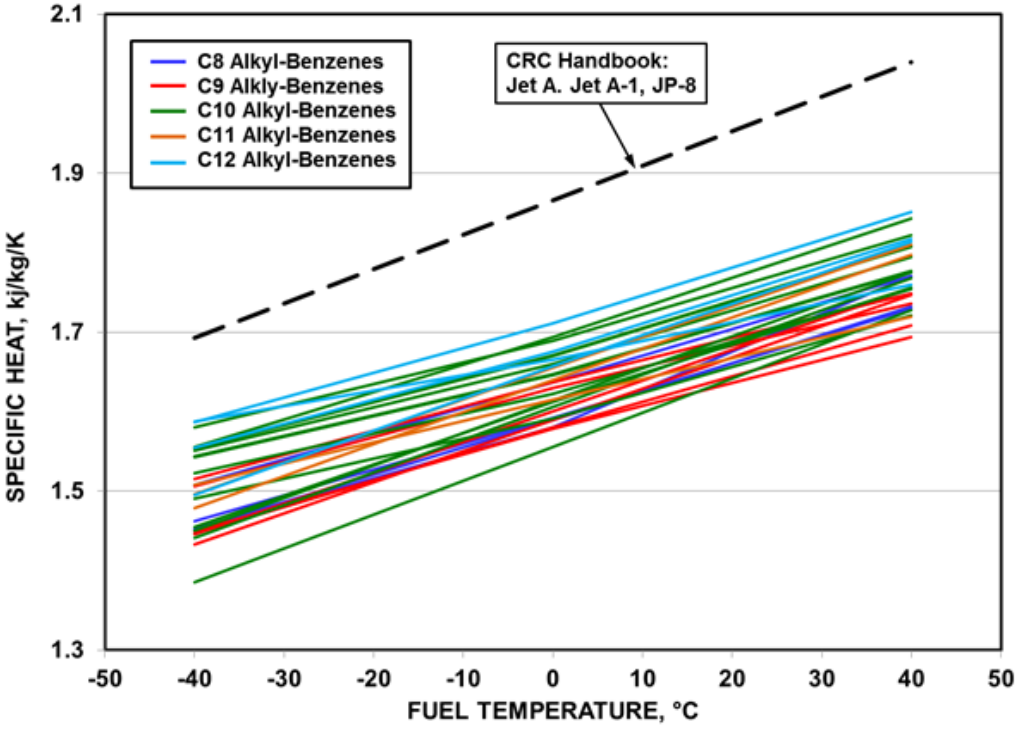


A1-4b. Iso-Paraffins

Figure A1-4. Specific Heat of Pure Hydrocarbons

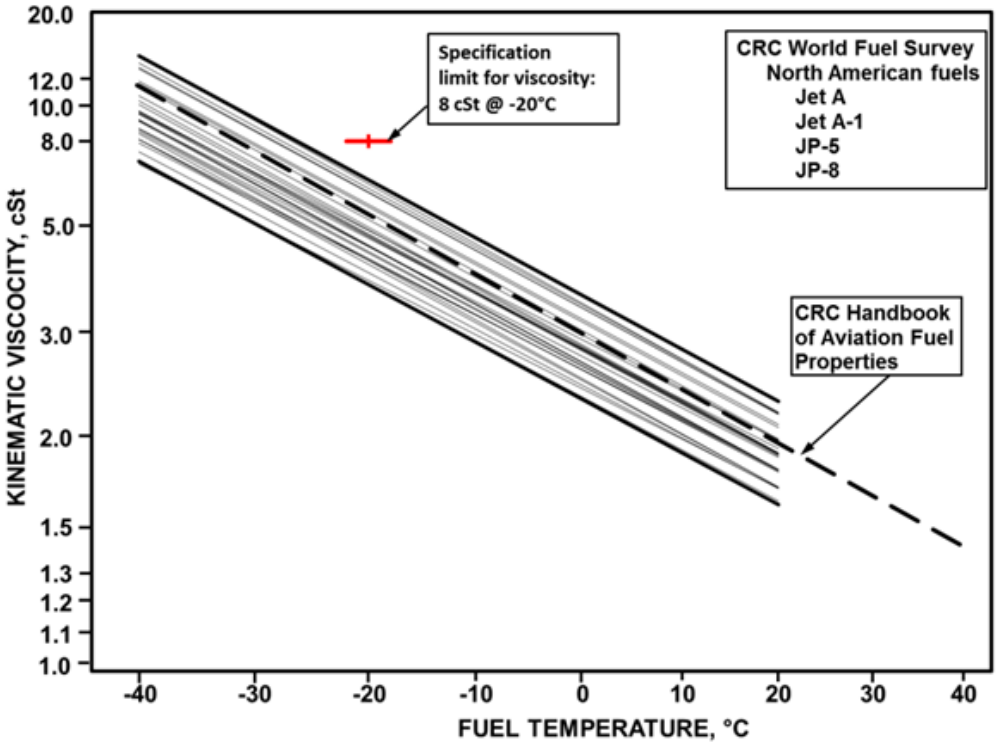


A1-4c. Cyclo-Paraffins

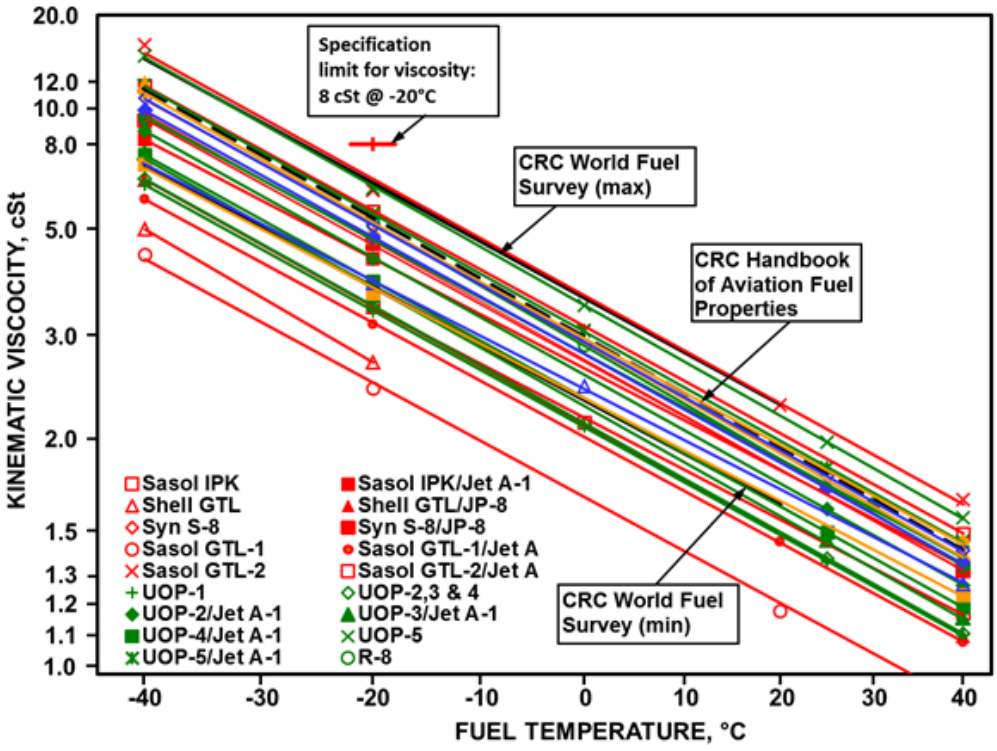


A1-4d. Aromatics

Figure A1-4. Specific Heat of Pure Hydrocarbons (continued)

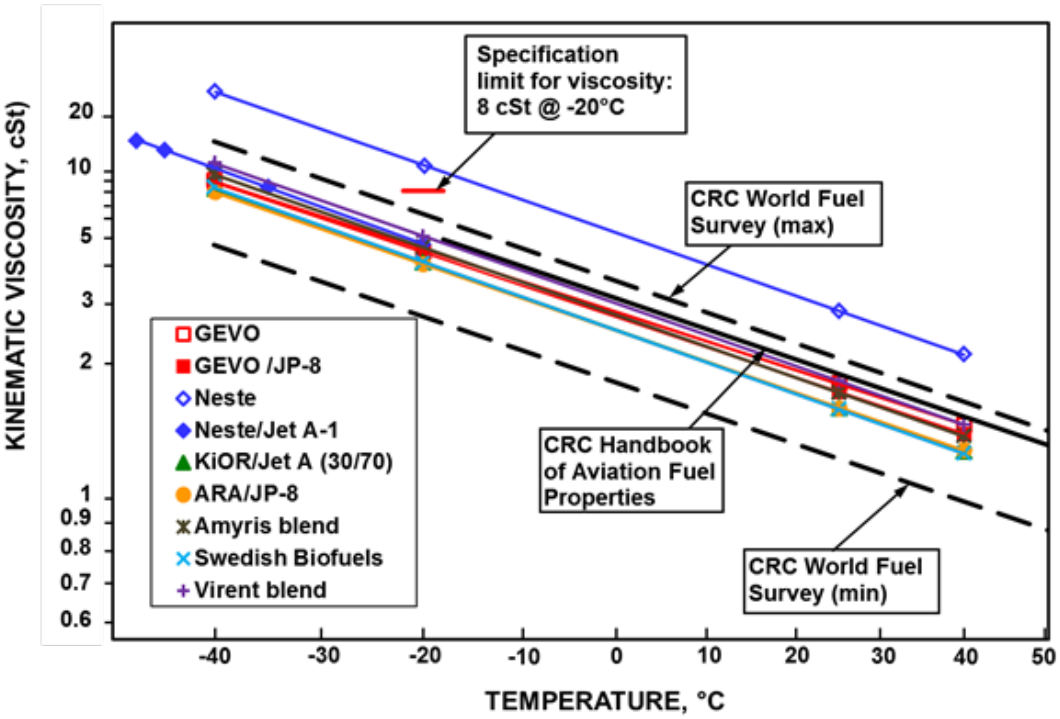


A1-5a. CRC World Fuel Survey

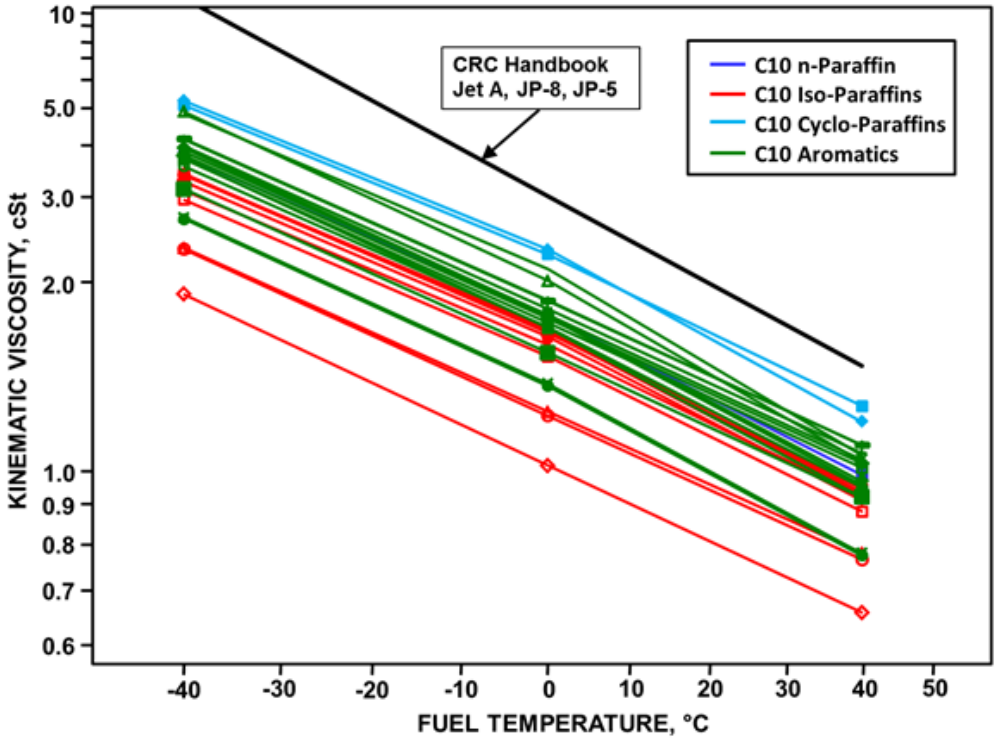


A1-5b. F-T and HEFA Fuels and Blends

Figure A1-5. Kinematic Viscosity of Hydrocarbon Fuels

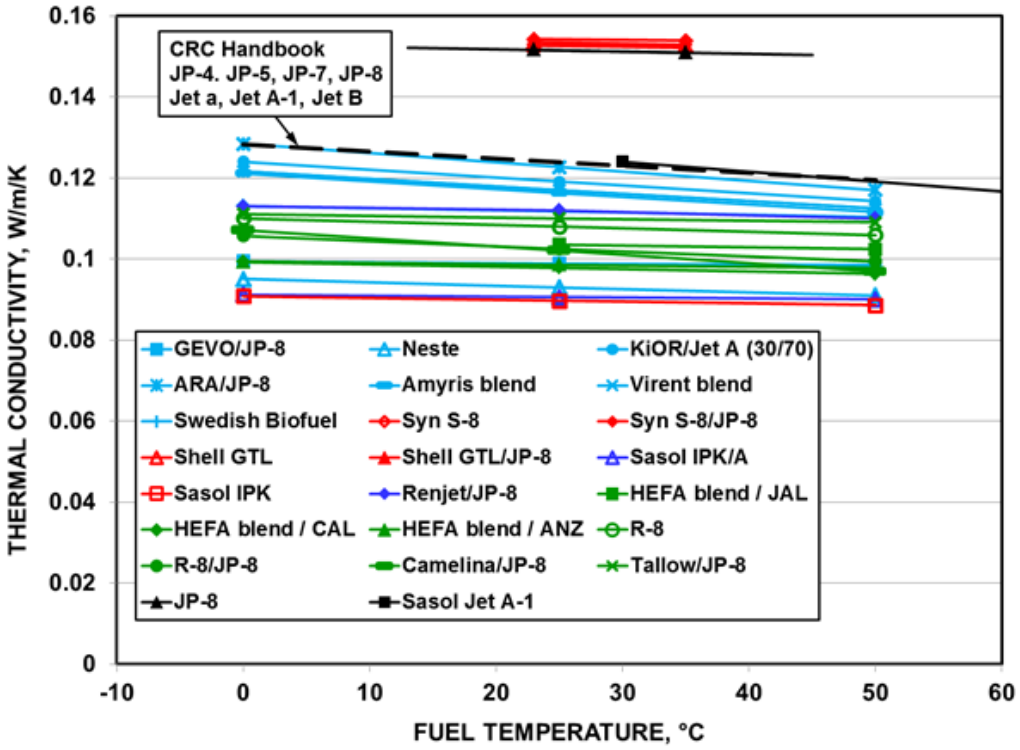


A1-5c. 2nd-Generation Renewable Fuels

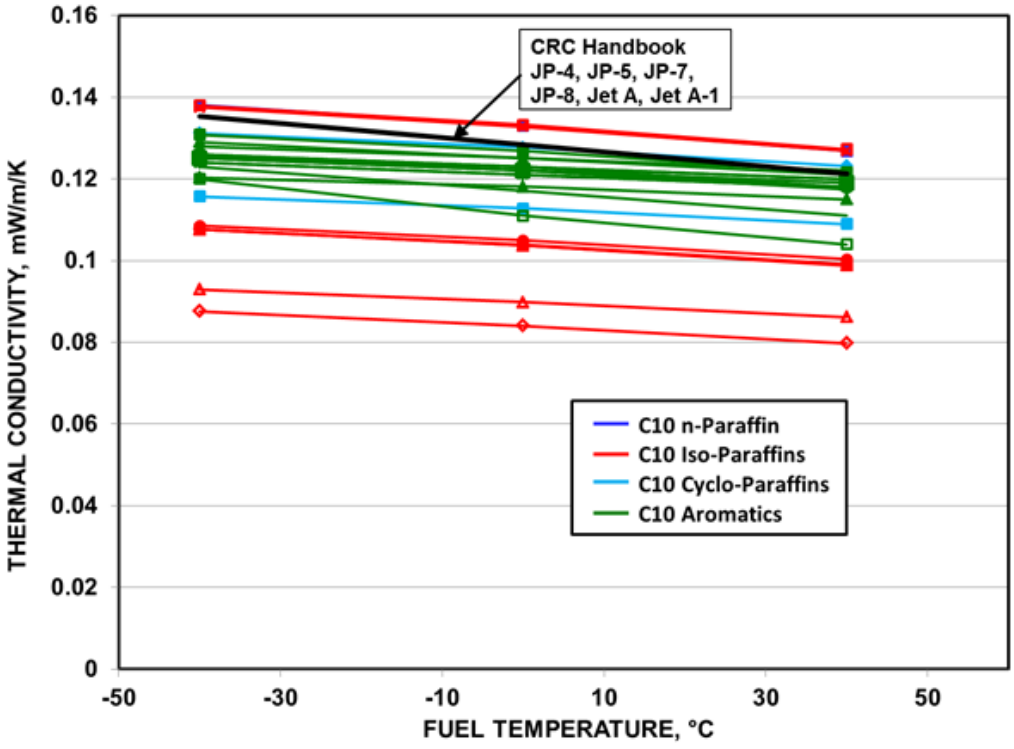


A1-5d. C10 Pure Hydrocarbons

Figure A1-5. Kinematic Viscosity of Hydrocarbon Fuels

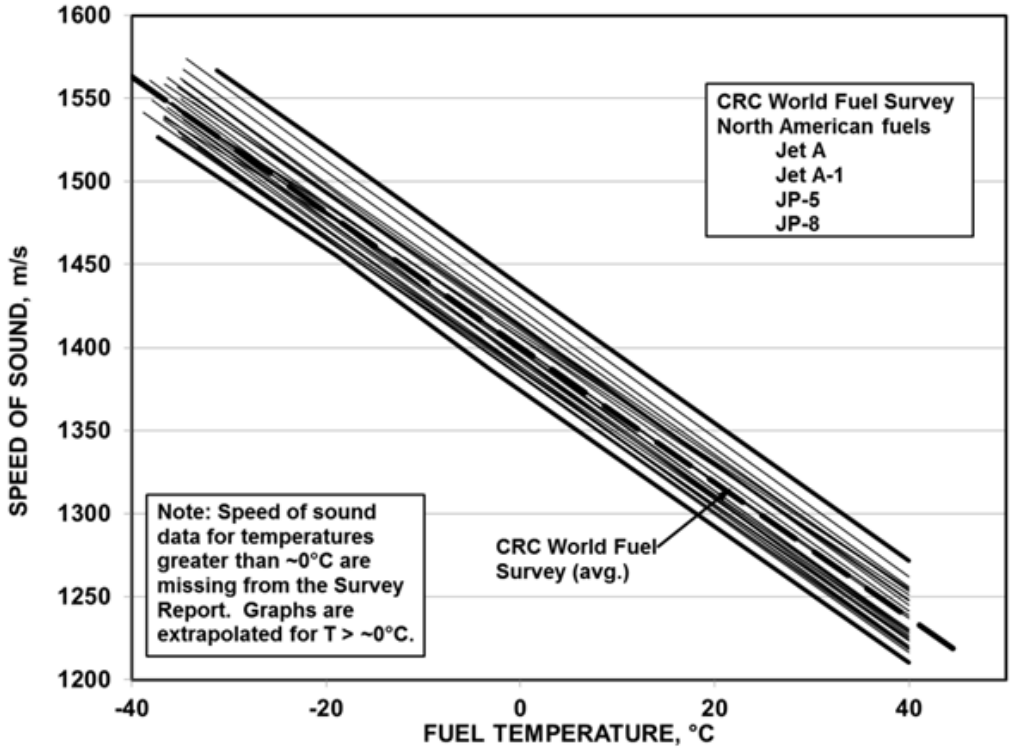


A1-6a. All Synthesized Fuels and Blends

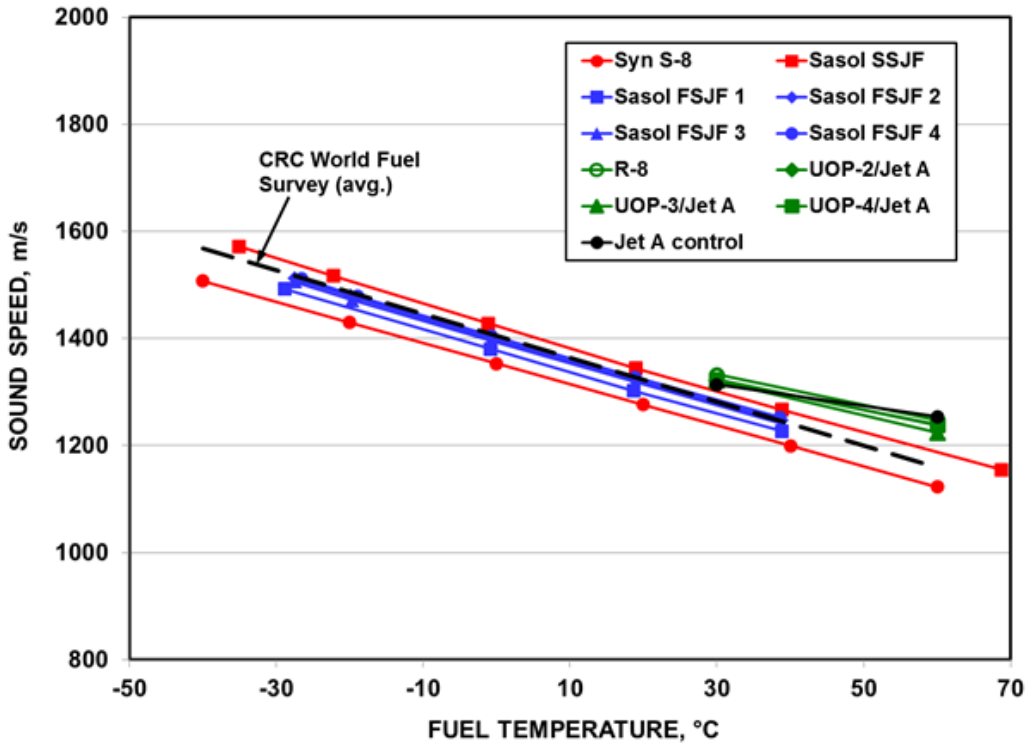


A1-6b. Pure C10 Hydrocarbons

Figure A1-6. Thermal Conductivity of Hydrocarbon Fuels

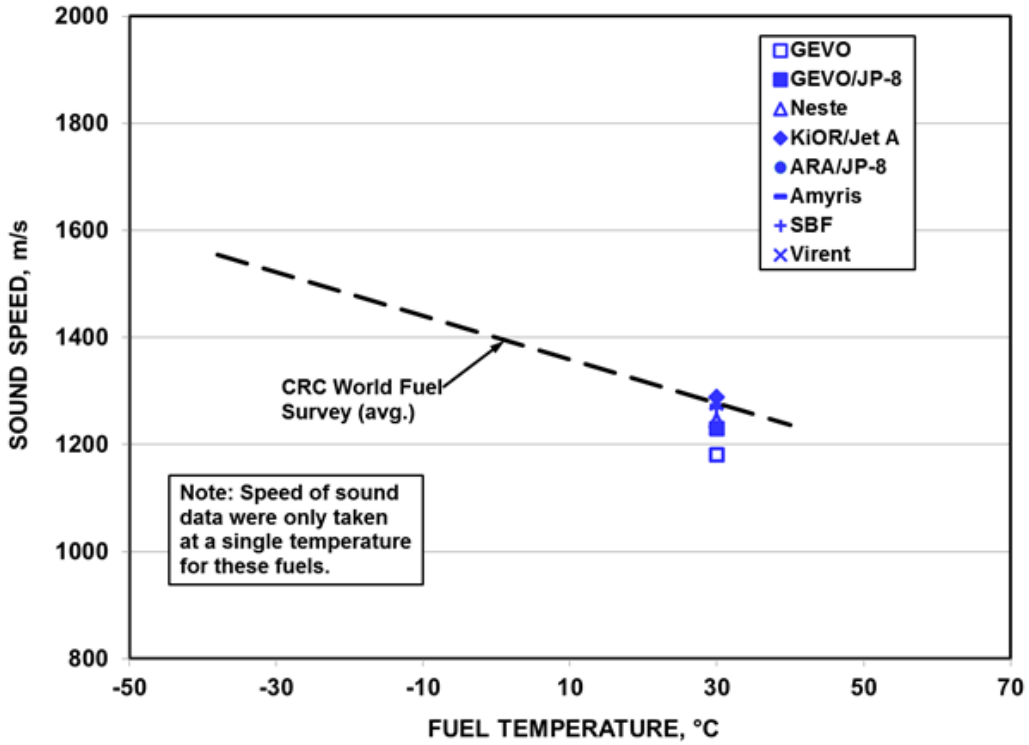


A1-7a. CRC World Fuel Survey

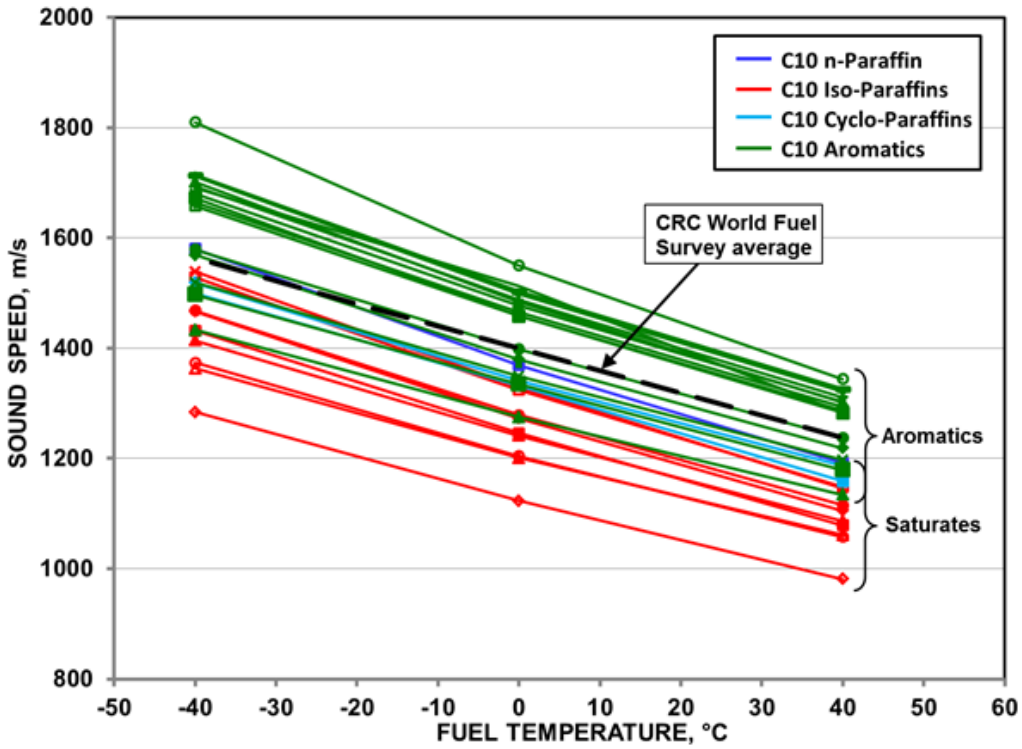


A1-7b. F-T and HEFA Fuels and Blends

Figure A1-7. Speed of Sound of Hydrocarbon Fuels

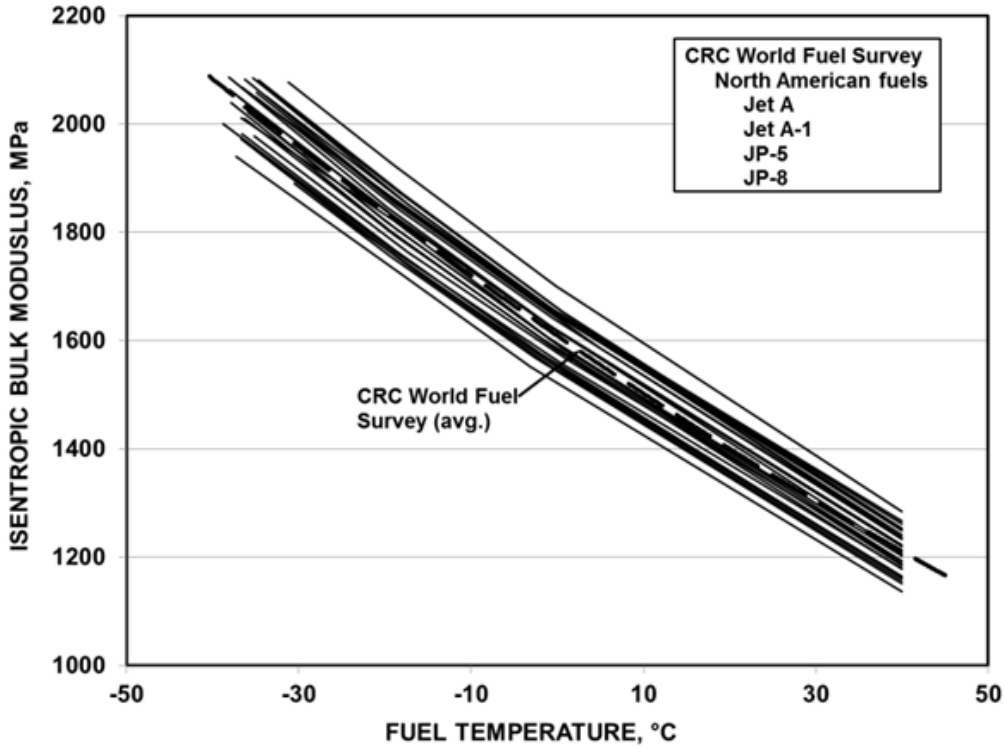


A1-7c. 2nd Generation Renewable Fuels and Blends

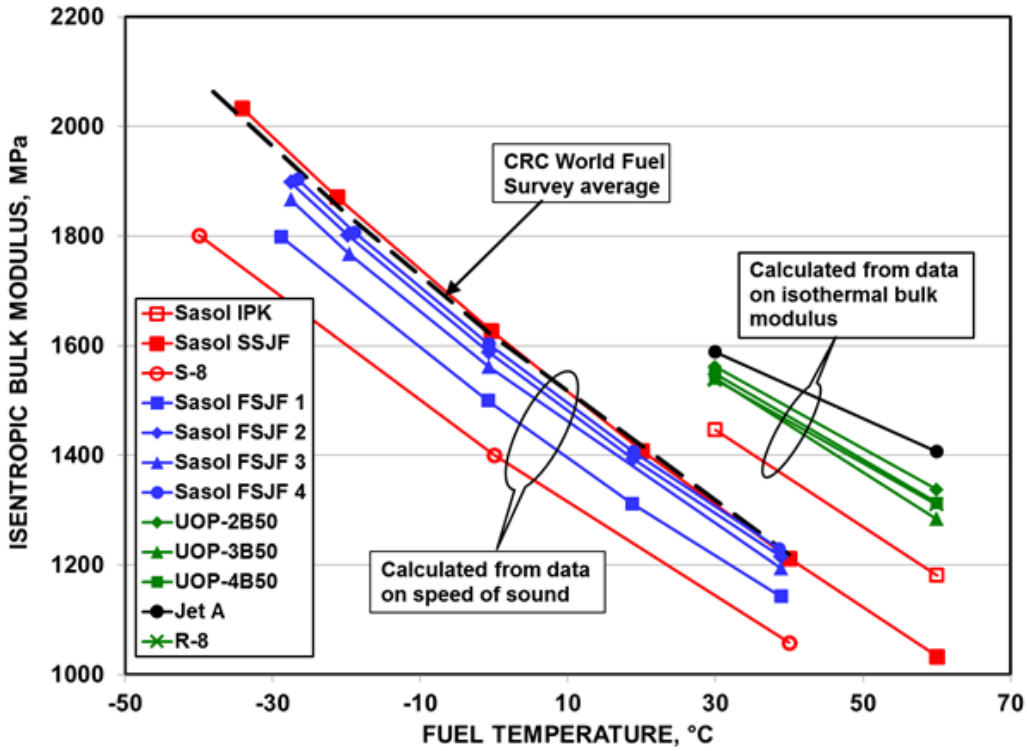


A1-7d. C10 Pure Hydrocarbons

Figure A1-7. Speed of Sound of Hydrocarbon Fuels (continued)

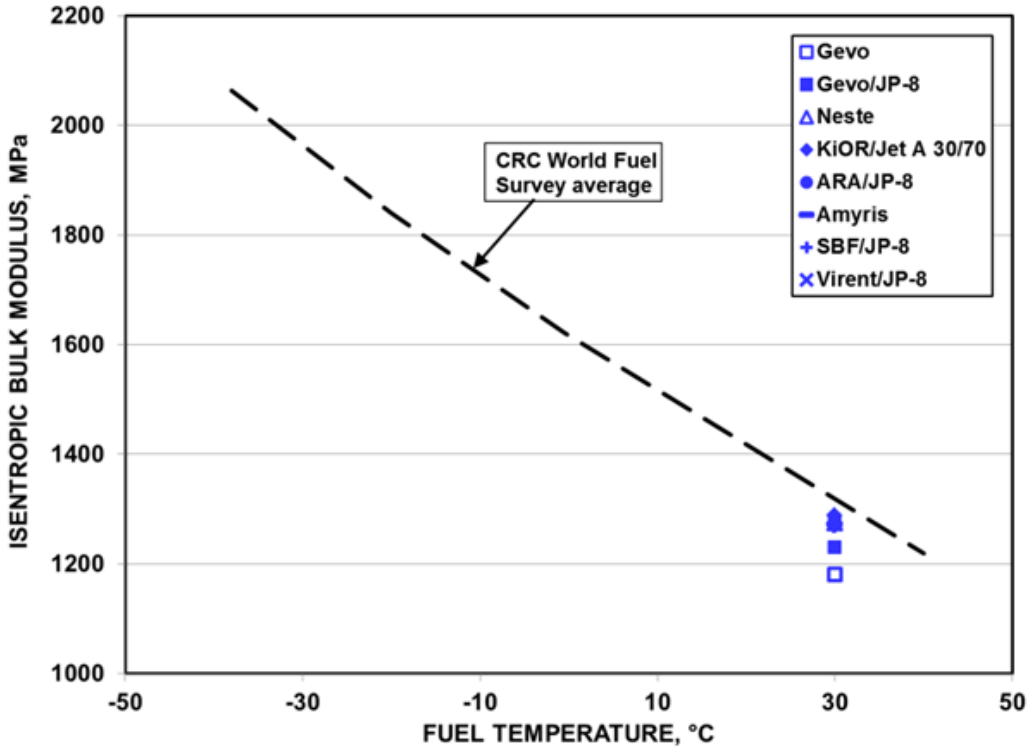


A1-8a. CRC World Fuel Survey

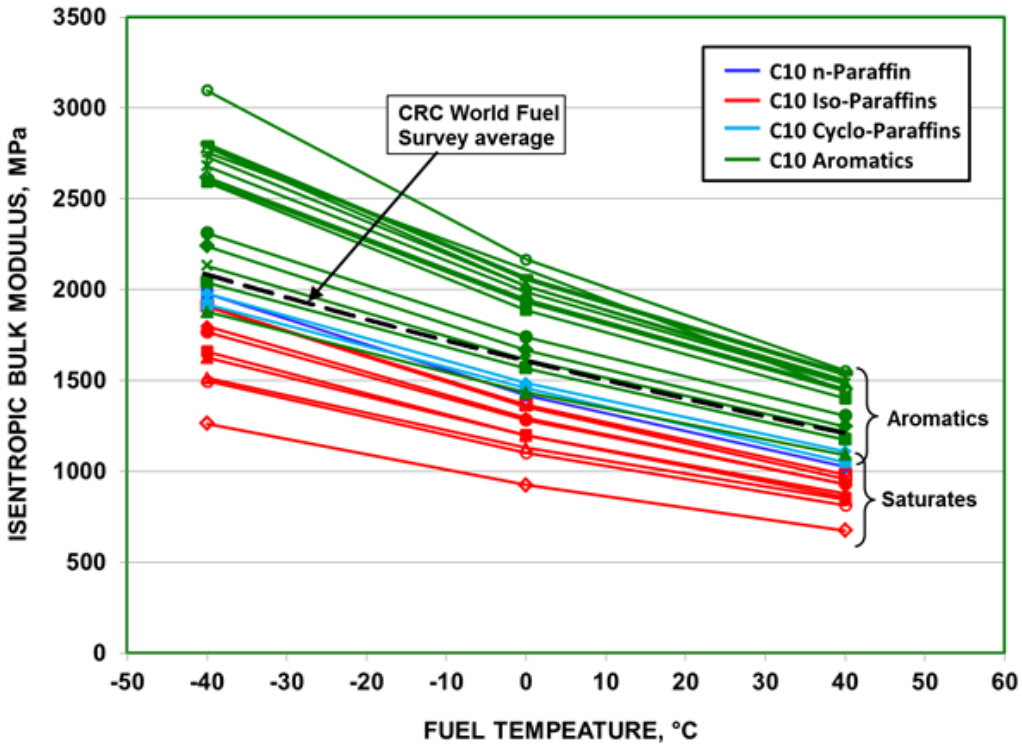


A1-8b. F-T and HEFA Fuels and Blends

Figure A1-8. Isentropic Bulk Modulus of Hydrocarbon Fuels

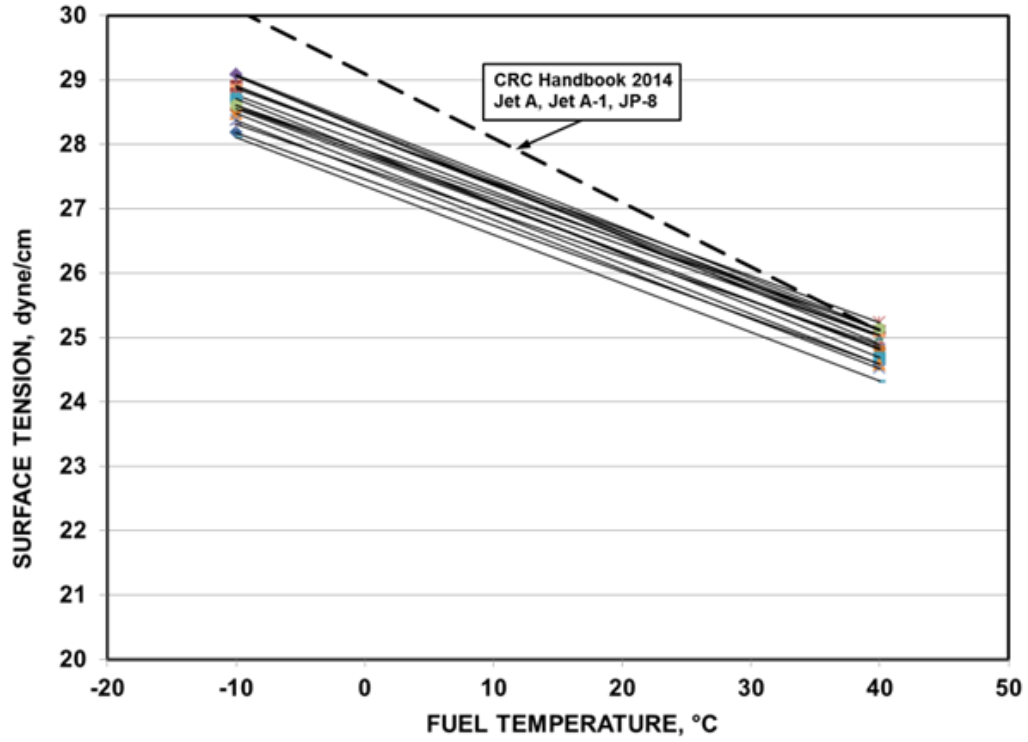


A1-8c. 2nd Generation Renewable Fuels and Blends

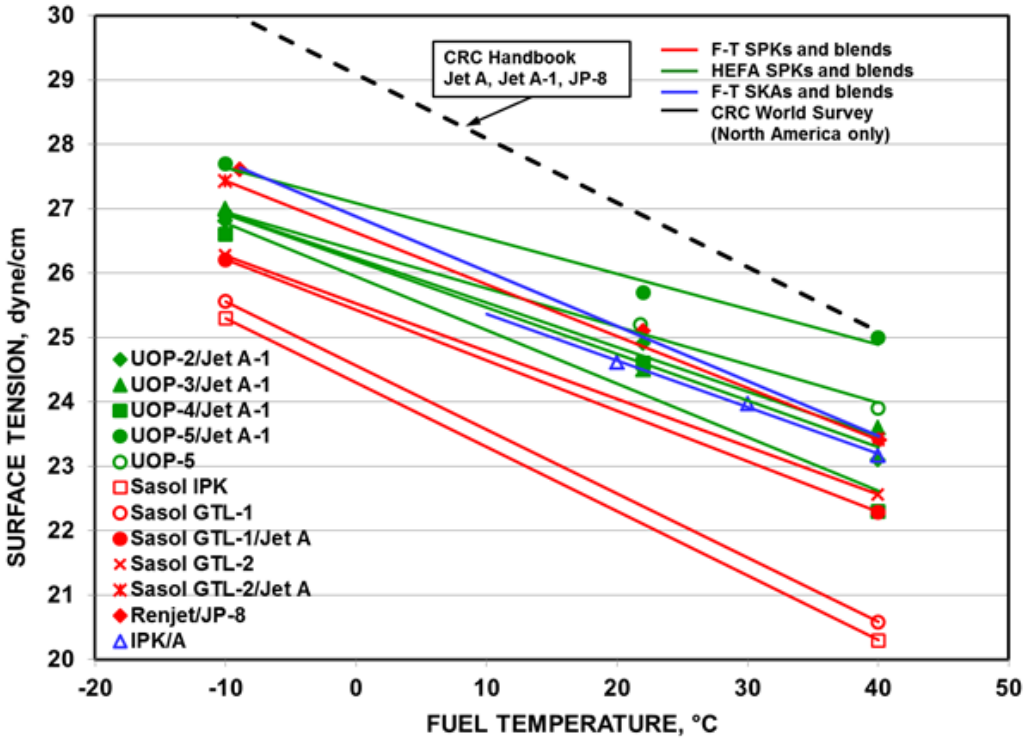


A1-8d. C10 Pure Hydrocarbons

Figure A1-8. Isentropic Bulk Modulus of Hydrocarbon Fuels (continued)

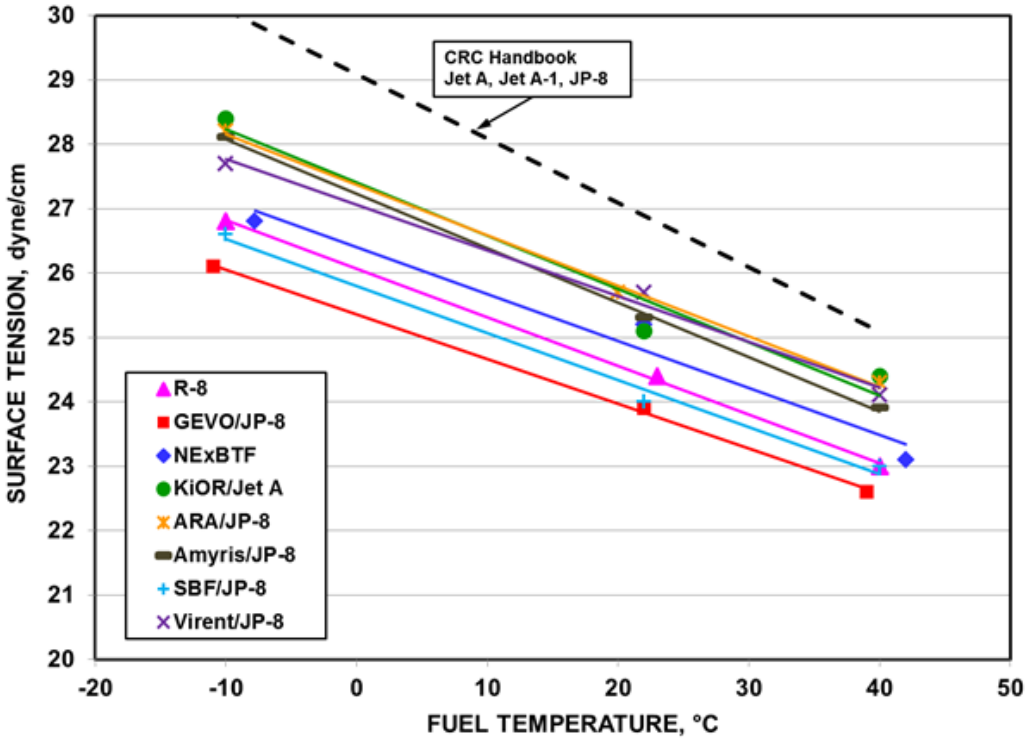


A1-9a. CRC World Fuel Survey

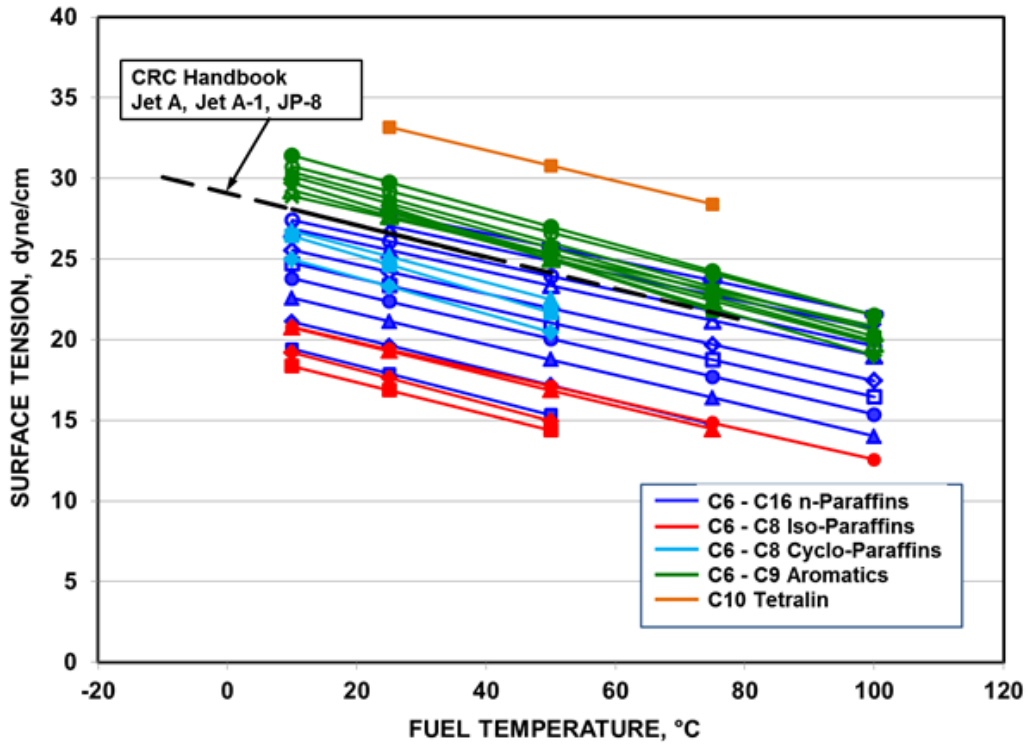


A1-9b. F-T and HEFA Fuels and Blends

Figure A1-9. Surface Tension of Hydrocarbon Fuels

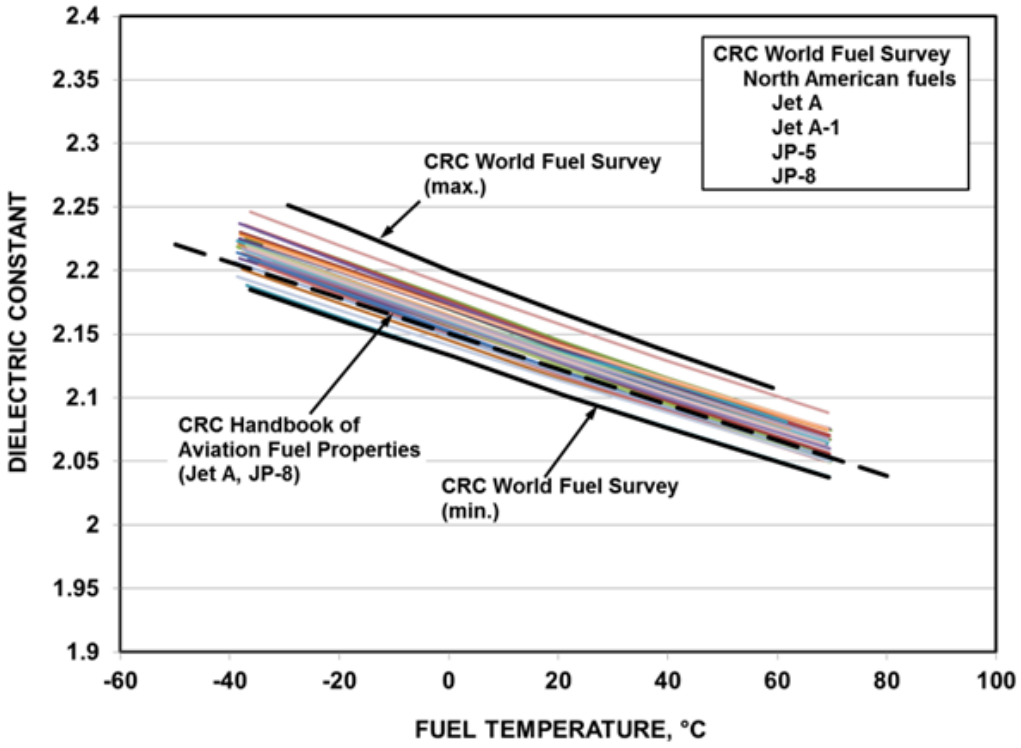


A1-9c. 2nd Generation Renewable Fuels and Blends

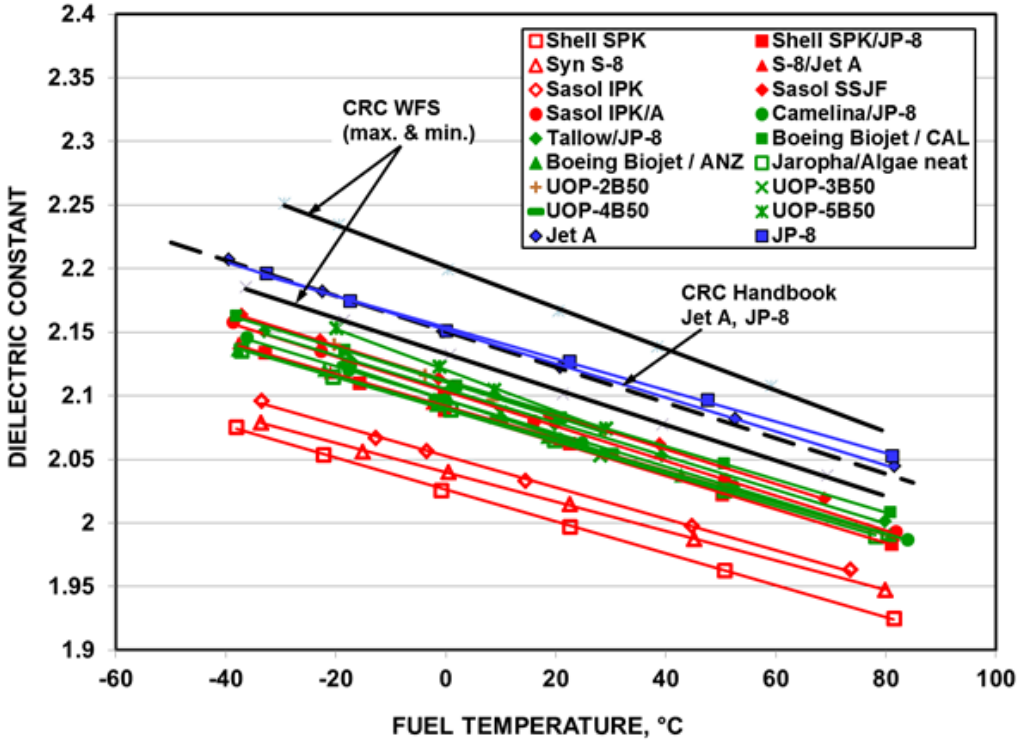


A1-9d. C10 Pure Hydrocarbons

Figure A1-9. Surface Tension of Hydrocarbon Fuels (continued)

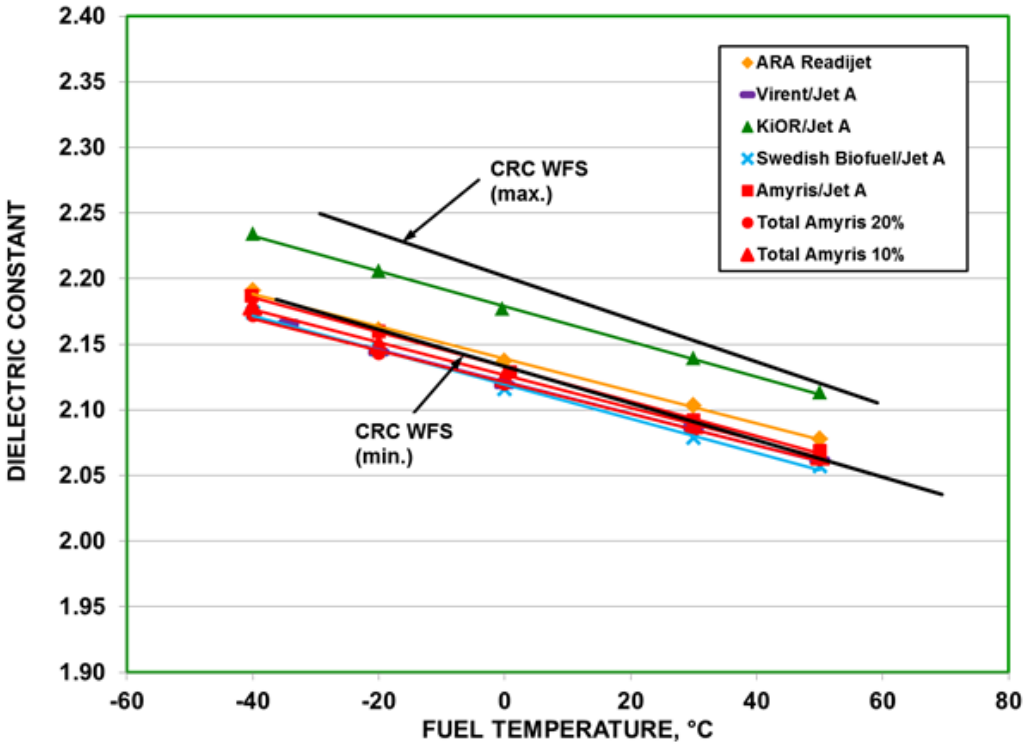


A1-10a. CRC World Fuel Survey

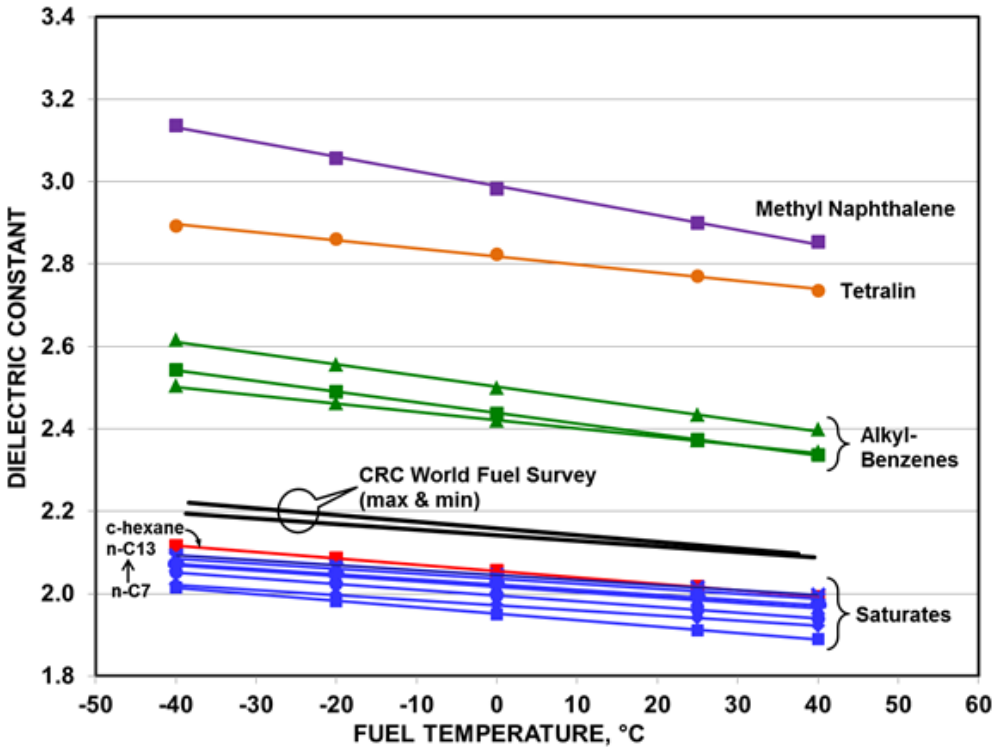


A1-10b. F-T and HEFA Fuels and Blends

Figure A1-10. Dielectric Constant of Hydrocarbon Fuels

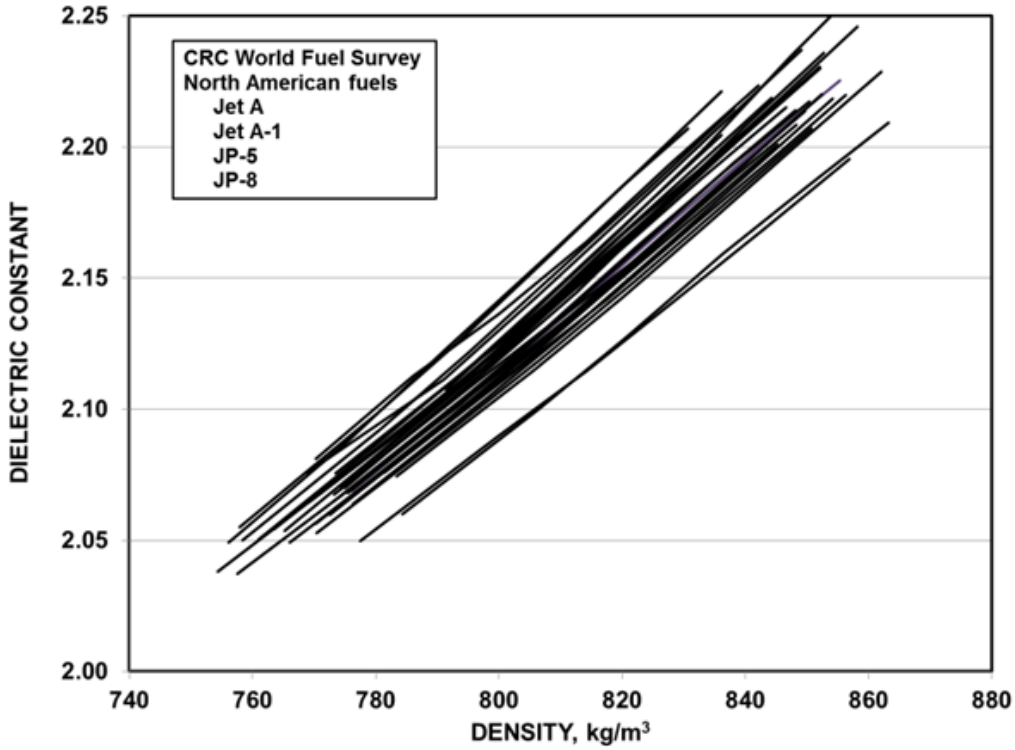


A1-10c. 2nd Generation Renewable Fuels and Blends

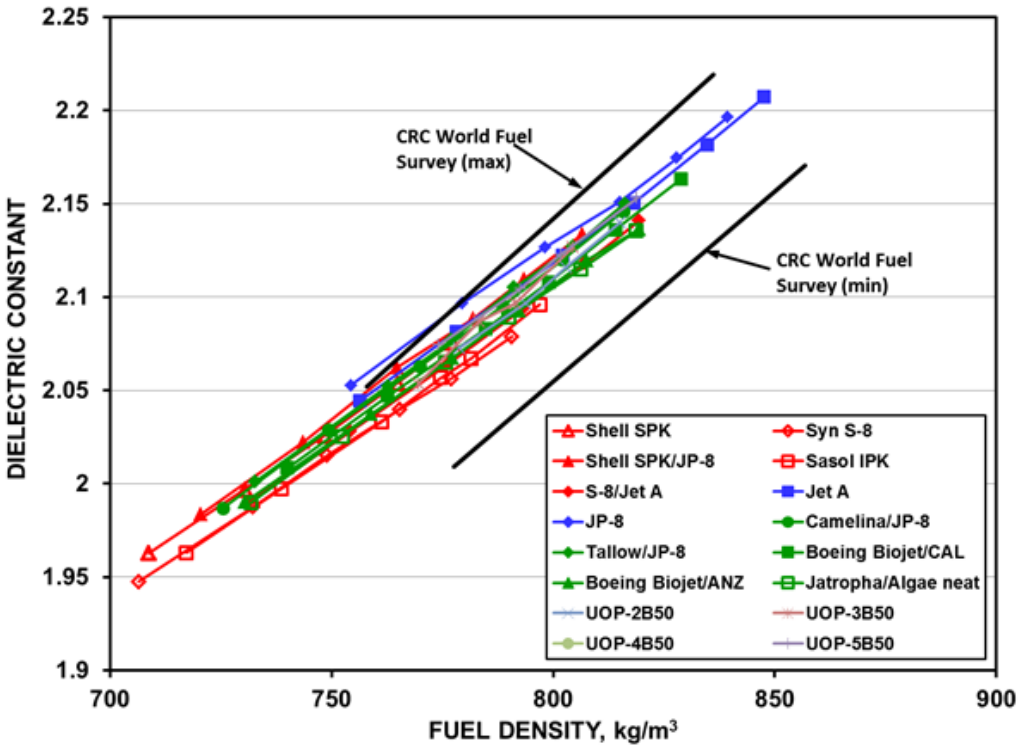


A1-10d. C10 Pure Hydrocarbons

Figure A1-10. Dielectric Constant of Hydrocarbon Fuels (continued)

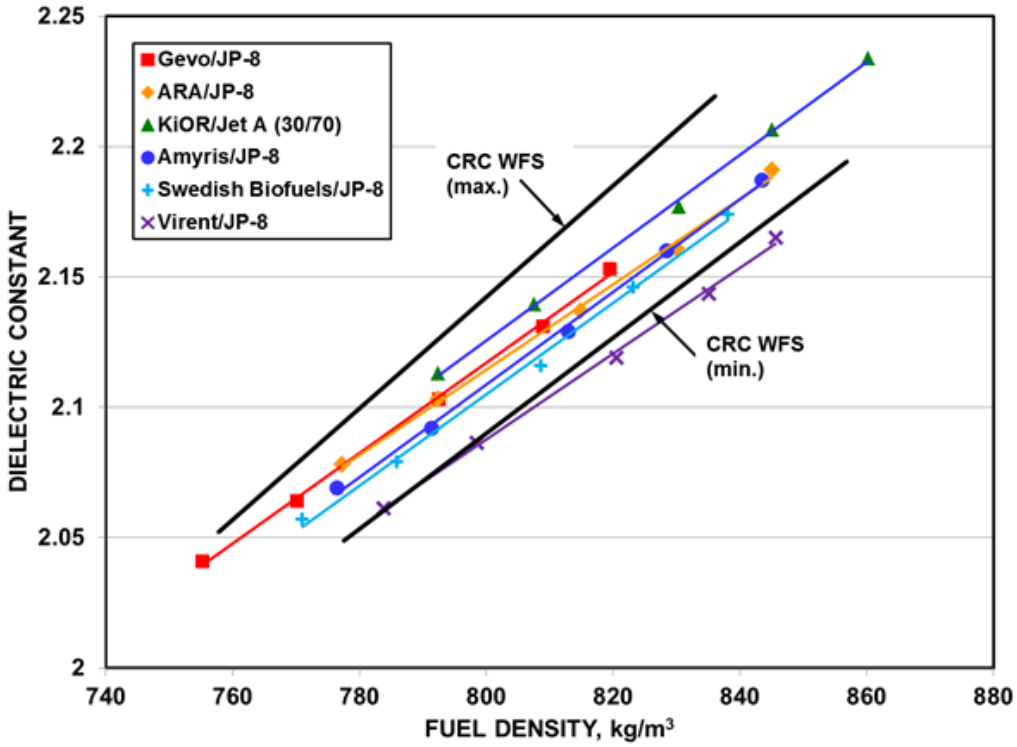


A1-11a. CRC World Fuel Survey

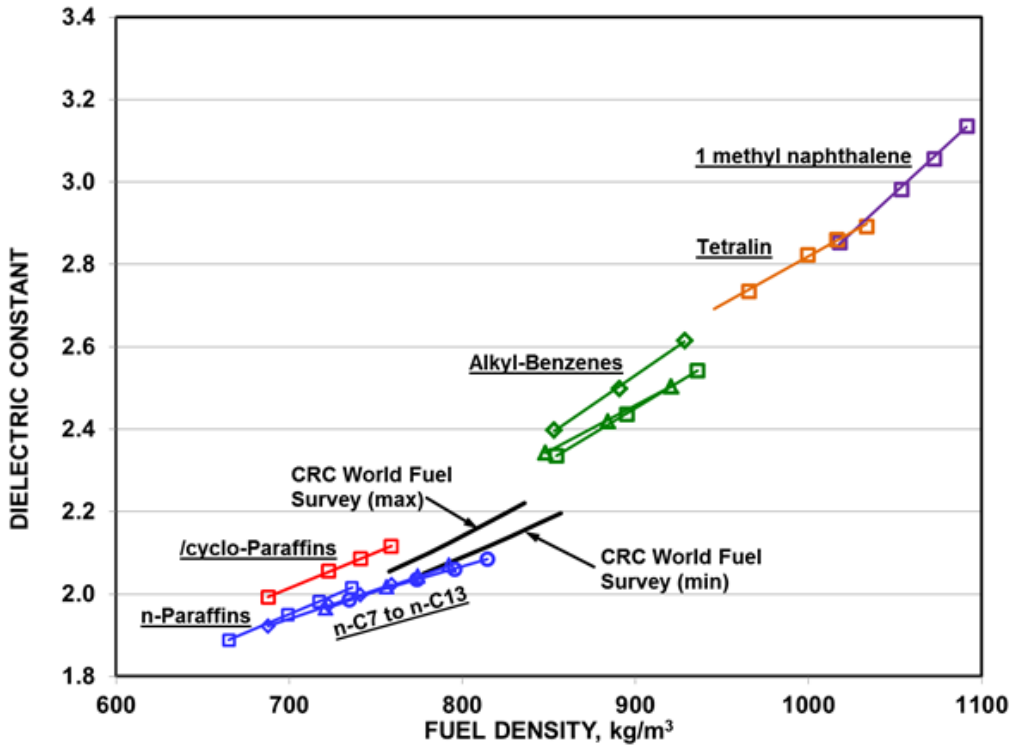


A1-11b. F-T and HEFA Fuels and Blends

Figure A1-11. Dielectric-Density Correlation for Hydrocarbon Fuels

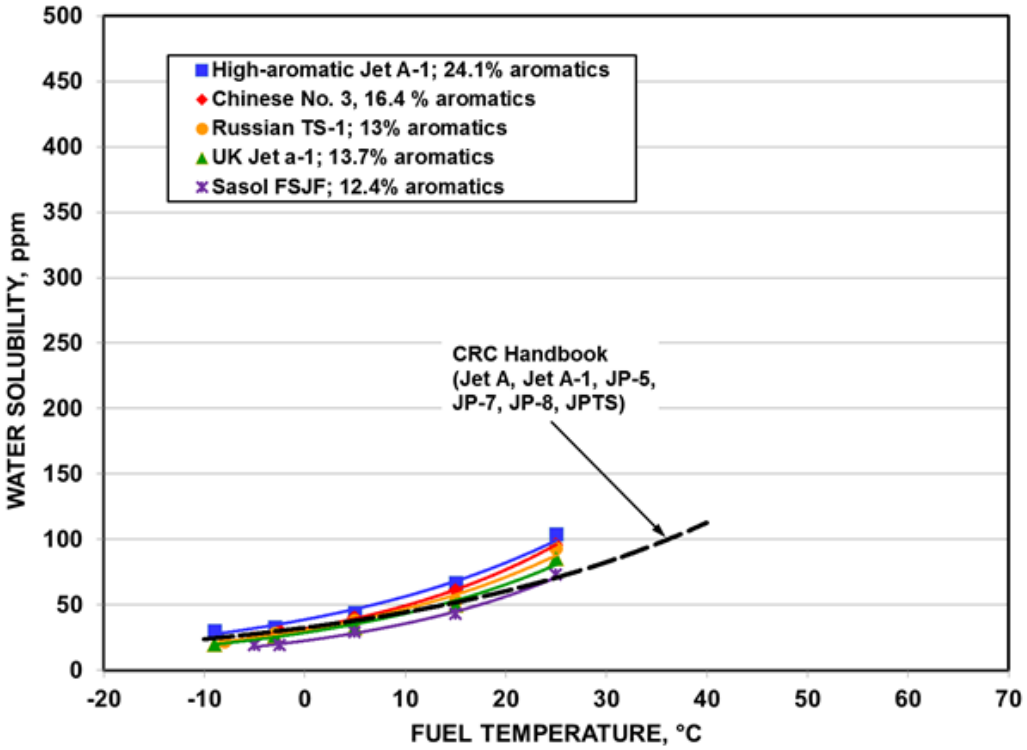


A1-11c. 2nd Generation Renewable Fuels and Blends

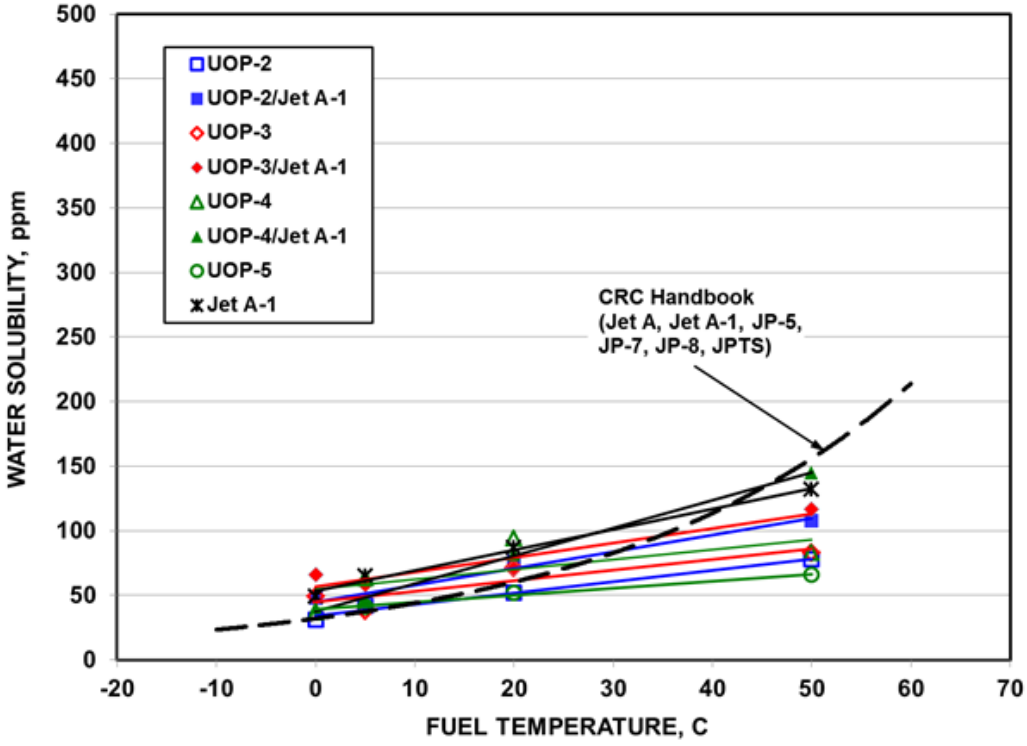


A1-11d. C10 Pure Hydrocarbons

Figure A1-11. Dielectric-Density Correlation for Hydrocarbon Fuels (continued)

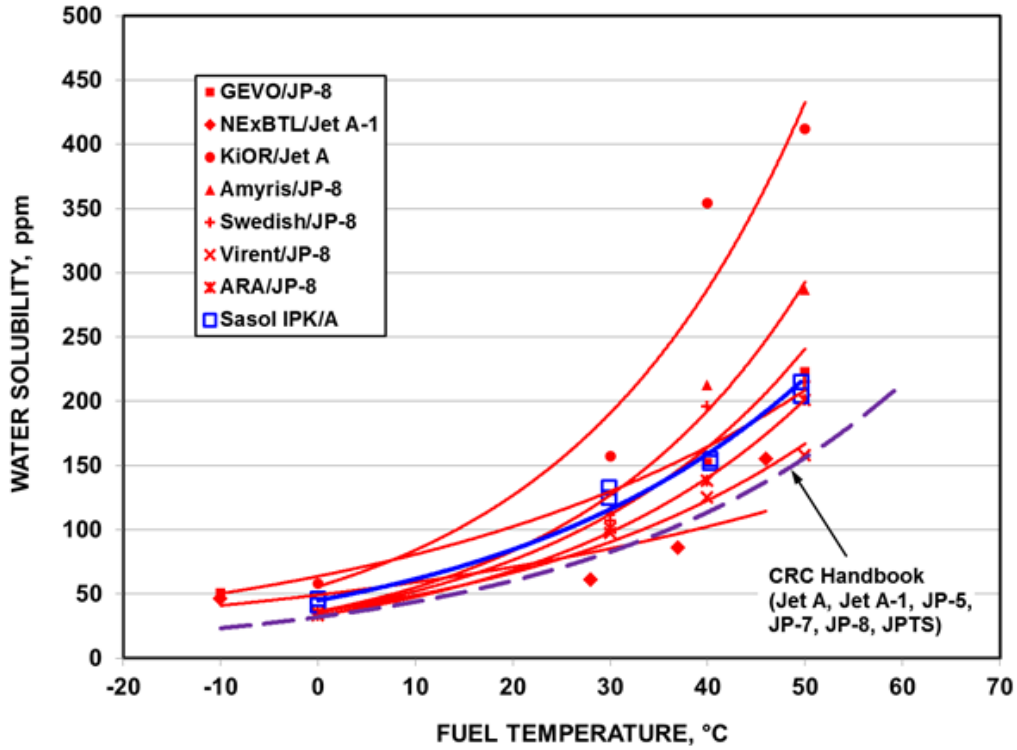


A1-12a. EASA Fuels



A1-12b. HEFA Fuels and Blends

Figure A1-12. Water Solubility in Hydrocarbon Fuels



A1-12c. 2nd Generation Renewable Fuels and Blends

Figure A1-12. Water Solubility in Hydrocarbon Fuels (continued)

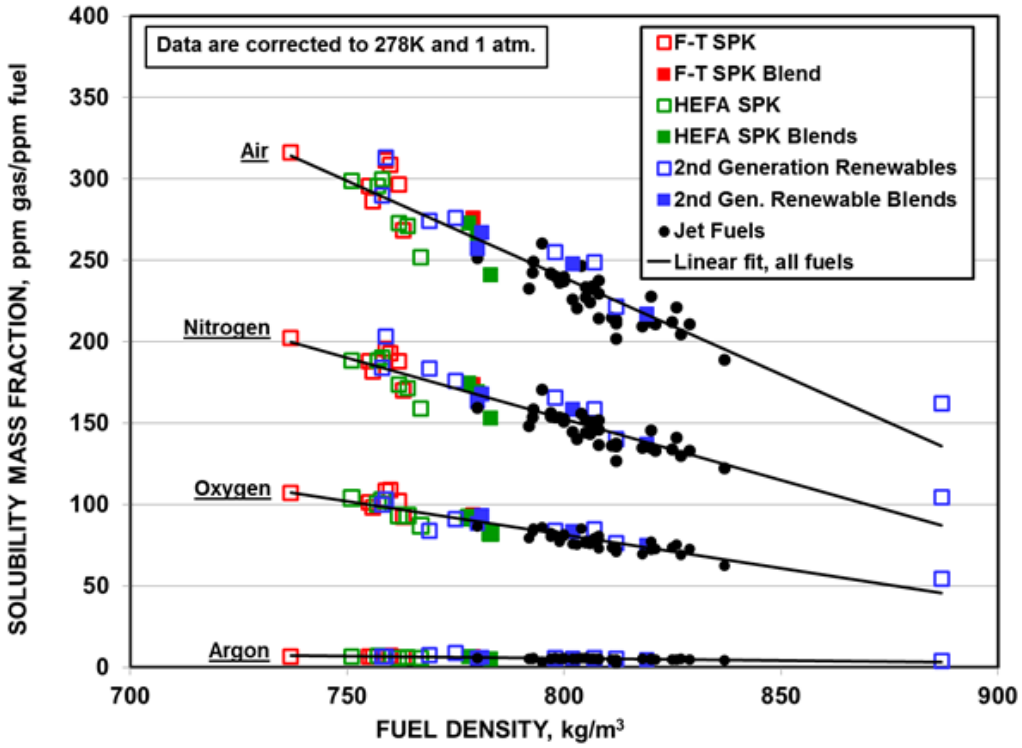


Figure A1-13. Solubility of N_2, O_2, and Argon in Hydrocarbon Fuels (with Air Ullage)

Table A2-1a. Hydrocarbon Composition of CRC World Fuel Survey – Aromatics

POSF Number	3895	3896	3897	3898	3899	3900	3901	3902	3938	3939	3940	3941	3960	3961	3962	3963	3964	3965
Fuel Type	JP-8	JP-8	JP-8	JP-8	JETA	JP-8	JETA	JP-8	JP-8	JP-5	JP-5	JETA-1	JETA	JETA	JETA	JETA-1	JETA	JETA-1
World Survey Number	34	35	32	33	7	31	6	30	42	39	40	325	18	20	3	318	8	306
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
Alkylbenzenes																		
benzene (C06)	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.06	<0.01	<0.01	<0.01	0.01	<0.01
toluene (C07)	0.08	0.04	0.11	0.13	0.03	0.16	0.06	0.10	0.06	0.05	0.01	0.26	0.35	0.12	0.11	0.07	0.13	0.31
C2-benzene (C08)	0.50	1.58	0.85	0.96	0.21	1.01	0.39	0.82	0.67	0.48	0.22	1.58	1.21	0.96	0.62	0.75	0.88	1.48
C3-benzene (C09)	2.11	4.53	2.66	2.48	0.55	4.89	1.29	3.46	2.62	1.39	1.40	4.44	2.51	2.19	2.22	5.28	2.94	3.91
C4-benzene (C10)	2.82	3.60	3.53	3.27	1.28	4.53	2.30	4.17	4.02	2.32	3.23	4.42	2.99	2.18	3.06	5.44	3.25	3.18
C5-benzene (C11)	1.86	2.32	3.29	2.39	1.98	2.78	2.33	2.91	3.33	2.23	2.58	2.71	2.22	1.33	2.51	2.26	2.15	1.92
C6-benzene (C12)	1.26	1.62	2.48	1.60	1.91	1.85	1.72	2.03	2.38	1.77	2.00	1.60	1.69	0.91	1.94	1.12	1.48	1.27
C7-benzene (C13)	0.80	1.18	1.27	0.73	1.18	1.07	1.07	1.25	1.18	1.29	1.21	0.53	1.00	0.49	1.15	0.56	1.00	0.65
C8-benzene (C14)	0.55	0.76	0.63	0.34	0.90	0.65	0.88	0.77	0.56	1.17	0.94	0.15	0.84	0.35	0.89	0.33	0.72	0.44
C9-benzene (C15)	0.24	0.40	0.20	0.09	0.49	0.26	0.49	0.27	0.20	0.50	0.49	0.05	0.55	0.25	0.57	0.12	0.39	0.19
C10+-benzene (C16+)	0.05	0.19	0.07	<0.01	0.10	0.07	0.12	0.09	0.07	0.03	0.16	0.02	0.28	0.08	0.23	0.02	0.21	0.06
Total Alkylbenzenes	**10.28**	**16.22**	**15.10**	**11.99**	8.62	**17.29**	**10.66**	**15.87**	**15.08**	**11.22**	**12.24**	**15.75**	**13.71**	**8.87**	**13.32**	**15.96**	**13.17**	**13.41**
Diaromatics (Naphthalenes, Biphenyls, etc.)																		
diaromatic-C10	0.15	0.20	0.09	0.46	0.28	0.15	0.29	0.06	0.09	0.13	0.54	0.48	0.44	0.02	0.20	0.18	0.07	0.34
diaromatic-C11	0.59	0.53	0.30	1.16	0.95	0.63	0.95	0.26	0.30	0.42	1.48	0.91	1.15	0.02	0.66	0.39	0.24	0.94
diaromatic-C12	0.91	0.83	0.45	0.98	1.32	1.01	1.40	0.51	0.42	0.71	1.75	0.39	1.38	0.04	1.00	0.46	0.38	0.94
diaromatic-C13	0.37	0.52	0.25	0.21	0.70	0.42	0.75	0.23	0.18	0.39	0.77	0.08	0.72	0.03	0.61	0.18	0.21	0.33
diaromatic-C14+	0.10	0.40	0.06	0.03	0.22	0.11	0.25	0.07	0.06	0.05	0.29	0.02	0.41	0.02	0.31	0.04	0.13	0.11
Total Alkylnaphthalenes	**2.13**	**2.48**	**1.16**	**2.84**	3.46	**2.33**	**3.65**	**1.13**	**1.04**	**1.70**	**4.83**	**1.89**	**4.10**	**0.14**	**2.77**	**1.26**	**1.03**	**2.66**
Cycloaromatics (Indans, Tetralins,etc.)																		
cycloaromatic-C09	0.04	0.12	0.11	0.06	0.03	0.06	0.04	0.05	0.08	0.03	0.04	0.10	0.05	0.14	0.07	0.26	0.09	0.05
cycloaromatic-C10	0.43	0.68	1.22	0.65	0.56	0.39	0.47	0.48	0.85	0.57	0.53	0.67	0.45	0.85	0.60	1.06	0.69	0.36
cycloaromatic-C11	0.93	1.80	2.17	1.27	1.74	0.81	1.13	1.32	1.69	1.57	1.05	1.08	0.87	1.30	1.31	1.23	1.52	0.68
cycloaromatic-C12	1.25	2.07	1.55	1.46	1.79	1.01	1.58	1.76	1.41	2.28	1.45	1.08	1.23	1.27	1.58	0.90	1.79	0.93
cycloaromatic-C13	1.16	1.39	0.98	1.18	1.61	0.92	1.61	1.25	0.95	2.28	1.81	0.56	1.40	1.09	1.63	0.63	1.25	0.96
cycloaromatic-C14	0.47	0.69	0.27	0.32	0.82	0.35	0.91	0.37	0.25	1.16	0.85	0.11	0.78	0.58	0.86	0.23	0.52	0.37
cycloaromatics-C15+	0.13	0.40	0.08	0.03	0.27	0.10	0.34	0.10	0.08	0.18	0.37	0.02	0.47	0.25	0.42	0.04	0.31	0.12
Total Cycloaromatics	**4.41**	**7.15**	**6.38**	**4.97**	6.81	**3.64**	**6.08**	**5.33**	**5.31**	**8.07**	**6.11**	**3.62**	**5.26**	**5.48**	**6.46**	**4.35**	**6.17**	**3.48**
Total Aromatics	**16.82**	**25.84**	**22.64**	**19.80**	**18.90**	**23.26**	**20.38**	**22.34**	**21.43**	**21.00**	**23.18**	**21.26**	**23.07**	**14.49**	**22.55**	**21.57**	**20.37**	**19.55**

Table A2-1b. Hydrocarbon Composition of CRC World Fuel Survey – Aromatics (continued)

POSF Number	3966	3967	3968	3969	3970	3971	4108	4109	4110	4111	4152	4153	4154	4155	4156	4158	4159	4195	4197
Fuel Type	JET A-1	JET A-1	JP-8	JET A-1	JP-8	TS-1	JET A	JET A	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	semi-syn	JET A-1	JP-8	JET A-1
World Survey Number	321	301	41	716	53	403	17	14	2	4	711	721	704	717	718	507	720	43	304
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
Alkylbenzenes																			
benzene (C06)	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
toluene (C07)	0.18	0.16	0.17	0.19	0.14	0.26	0.18	0.06	0.12	0.24	0.26	0.03	0.12	0.15	0.18	0.06	<0.01	0.04	0.23
C2-benzene (C08)	2.01	1.39	1.15	2.21	0.83	0.89	0.99	0.63	1.06	1.12	1.87	2.19	1.35	1.23	0.96	0.42	1.90	0.35	1.64
C3-benzene (C09)	4.40	3.72	3.53	4.03	3.08	2.18	2.41	2.39	3.70	3.10	5.38	4.66	4.40	4.63	2.84	2.28	5.64	1.41	4.08
C4-benzene (C10)	3.66	3.66	3.90	3.41	4.13	3.67	2.23	2.92	3.78	2.98	3.55	3.34	3.97	3.82	3.34	2.75	3.92	2.53	3.79
C5-benzene (C11)	2.30	2.30	2.74	2.12	3.14	2.88	1.78	2.32	2.53	1.96	2.03	1.67	2.38	2.35	2.20	1.73	2.04	2.20	2.46
C6-benzene (C12)	1.45	1.52	1.65	1.13	2.13	1.75	1.40	1.72	1.69	1.42	1.06	1.22	1.44	1.50	1.23	1.19	1.30	1.75	1.63
C7-benzene (C13)	0.79	0.92	0.83	0.51	1.23	0.69	0.95	1.02	0.92	0.81	0.39	0.43	0.64	0.86	0.38	0.67	0.37	0.96	0.98
C8-benzene (C14)	0.52	0.50	0.45	0.34	0.80	0.25	0.70	0.78	0.61	0.63	0.19	0.02	0.33	0.51	0.12	0.36	<0.01	0.79	0.61
C9-benzene (C15)	0.20	0.19	0.20	0.13	0.42	0.09	0.50	0.47	0.30	0.57	0.03	<0.01	0.14	0.19	0.02	0.13	<0.01	0.53	0.24
C10+-benzene (C16+)	0.07	0.05	0.08	0.03	0.17	0.02	0.39	0.27	0.13	0.40	<0.01	<0.01	0.05	0.08	<0.01	0.02	<0.01	0.37	0.07
Total Alkylbenzenes	**15.60**	**14.42**	**14.71**	**14.10**	**16.07**	**12.68**	**11.52**	**12.58**	**14.83**	**13.22**	**14.75**	**13.56**	**14.82**	**15.32**	**11.28**	**9.60**	**15.19**	**10.93**	**15.73**
Diaromatics (Naphthalenes, Biphenyls, etc.)																			
diaromatic-C10	0.22	0.15	0.24	0.35	0.11	0.17	0.20	0.26	0.15	0.25	0.52	0.03	0.08	0.12	0.50	0.10	<0.01	0.29	0.17
diaromatic-C11	0.63	0.39	0.63	0.92	0.42	0.37	0.54	0.75	0.51	0.70	1.17	0.05	0.20	0.40	1.15	0.33	0.02	0.79	0.43
diaromatic-C12	0.71	0.47	0.66	1.07	0.73	0.28	0.74	0.99	0.81	0.99	0.84	0.03	0.25	0.54	0.63	0.47	0.04	1.05	0.59
diaromatic-C13	0.28	0.19	0.29	0.39	0.38	0.08	0.47	0.54	0.36	0.63	0.14	<0.01	0.12	0.17	0.10	0.17	<0.01	0.60	0.25
diaromatic-C14+	0.10	0.08	0.15	0.13	0.18	0.02	0.40	0.32	0.17	0.56	0.02	<0.01	0.05	0.06	0.01	0.04	<0.01	0.39	0.10
Total Alkylnaphthalenes	**1.94**	**1.28**	**1.97**	**2.85**	**1.82**	**0.92**	**2.34**	**2.85**	**2.01**	**3.12**	**2.69**	**0.10**	**0.71**	**1.29**	**2.39**	**1.11**	**0.07**	**3.12**	**1.54**
Cycloaromatics (Indans, Tetralins,etc.)																			
cycloaromatic-C09	0.09	0.15	0.05	0.06	0.05	0.04	0.16	0.06	0.06	0.09	0.06	0.82	0.07	0.06	0.11	0.05	1.06	0.02	0.21
cycloaromatic-C10	0.54	0.81	0.48	0.33	0.53	0.54	1.09	0.51	0.51	0.61	0.29	2.49	0.47	0.43	0.70	0.28	3.09	0.19	1.02
cycloaromatic-C11	0.96	1.35	1.10	0.62	1.22	1.27	1.61	1.15	1.06	1.18	0.50	2.88	0.85	0.90	1.03	0.50	3.17	0.48	1.52
cycloaromatic-C12	1.12	1.27	1.27	0.89	1.51	1.26	1.23	1.57	1.38	1.26	0.73	1.14	0.78	1.19	0.91	0.73	1.16	0.82	1.32
cycloaromatic-C13	0.93	0.86	0.77	0.84	1.32	0.62	1.17	1.50	1.22	1.27	0.62	0.18	0.54	0.89	0.54	0.72	0.14	1.10	1.02
cycloaromatic-C14	0.33	0.30	0.31	0.37	0.58	0.15	0.65	0.74	0.50	0.82	0.14	<0.01	0.17	0.28	0.09	0.25	<0.01	0.64	0.37
cycloaromatics-C15+	0.11	0.09	0.15	0.10	0.25	0.03	0.54	0.46	0.20	0.59	0.01	<0.01	0.05	0.11	<0.01	0.05	<0.01	0.48	0.11
Total Cycloaromatics	**4.09**	**4.82**	**4.13**	**3.21**	**5.46**	**3.92**	**6.46**	**5.99**	**4.94**	**5.82**	**2.35**	**7.51**	**2.93**	**3.86**	**3.39**	**2.57**	**8.63**	**3.73**	**5.58**
Total Aromatics	**21.63**	**20.52**	**20.82**	**20.15**	**23.35**	**17.51**	**20.33**	**21.43**	**21.78**	**22.15**	**19.79**	**21.17**	**18.45**	**20.46**	**17.06**	**13.27**	**23.88**	**17.78**	**22.84**

Table A2-1c. Hydrocarbon Composition of CRC World Fuel Survey – Aromatics (continued)

POSF Number	4198	4324	4325	4326	4327	4363	4364	4365	4366	4368	4369	4370	4371	4384	4385	4386	4433	4461
Fuel Type	JET A-1	JET A-1	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1
World Survey Number	316	315	44	45	104	314	110	109	108	206	101	105	606	335	334	211	111	336
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
Alkylbenzenes																		
benzene (C06)	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.02	0.02	<0.01	<0.01	<0.01	0.01	<0.01
toluene (C07)	0.13	0.19	0.14	0.14	0.03	0.13	<0.01	0.12	0.17	0.14	0.10	0.15	0.16	0.10	0.17	0.05	0.11	0.07
C2-benzene (C08)	1.45	1.23	0.90	0.91	0.35	2.26	0.03	0.99	0.68	0.83	0.64	0.79	1.07	0.81	1.15	0.35	0.76	1.75
C3-benzene (C09)	5.68	3.96	3.15	3.15	1.47	4.35	1.48	3.24	1.69	5.46	2.97	2.42	5.24	3.73	3.60	2.22	1.53	5.16
C4-benzene (C10)	4.06	3.86	3.45	3.42	4.17	3.90	3.81	3.87	3.72	6.07	4.69	2.98	4.76	3.97	4.27	2.16	1.46	4.64
C5-benzene (C11)	2.16	2.37	2.48	2.47	2.95	2.41	2.72	2.70	2.59	3.46	2.75	2.15	2.71	2.64	2.85	1.48	1.13	2.51
C6-benzene (C12)	1.39	1.45	1.81	1.83	2.30	1.46	1.64	1.76	1.65	1.71	1.31	1.61	1.69	1.78	1.73	1.00	1.22	1.34
C7-benzene (C13)	0.71	0.78	1.02	1.03	1.44	0.73	0.93	0.78	1.01	0.51	0.45	1.04	0.96	1.10	0.62	0.74	1.15	0.53
C8-benzene (C14)	0.40	0.51	0.73	0.71	1.07	0.43	0.89	0.22	0.67	0.22	0.20	0.74	0.49	0.77	0.18	0.44	0.89	0.31
C9-benzene (C15)	0.14	0.22	0.48	0.45	0.66	0.19	0.70	0.03	0.24	0.09	0.09	0.56	0.11	0.34	0.04	0.12	0.82	0.18
C10+-benzene (C16+)	0.04	0.08	0.24	0.23	0.28	0.07	0.60	<0.01	0.13	0.02	0.02	0.45	<0.01	0.10	<0.01	0.02	0.63	0.14
Total Alkylbenzenes	**16.15**	**14.63**	**14.41**	**14.36**	**14.72**	**15.93**	**12.81**	**13.72**	**12.55**	**18.53**	**13.21**	**12.92**	**17.22**	**15.34**	**14.62**	**8.58**	**9.73**	**16.63**
Diaromatics (Naphthalenes, Biphenyls, etc.)																		
diaromatic-C10	0.08	0.24	0.24	0.24	0.24	0.18	0.05	0.42	0.11	0.09	0.37	0.17	0.16	0.14	0.42	0.14	0.02	0.14
diaromatic-C11	0.24	0.63	0.72	0.75	0.78	0.47	0.26	1.10	0.34	0.22	0.58	0.51	0.60	0.53	0.87	0.35	0.06	0.27
diaromatic-C12	0.34	0.73	0.97	0.99	1.22	0.54	0.59	0.65	0.59	0.20	0.42	0.78	0.81	0.89	0.40	0.47	0.19	0.29
diaromatic-C13	0.13	0.29	0.52	0.52	0.71	0.22	0.52	0.10	0.27	0.07	0.14	0.51	0.22	0.49	0.07	0.12	0.22	0.16
diaromatic-C14+	0.05	0.10	0.30	0.30	0.41	0.08	0.51	<0.01	0.24	0.01	0.04	0.48	0.03	0.19	0.01	0.02	0.37	0.16
Total Alkylnaphthalenes	**0.84**	**1.99**	**2.75**	**2.80**	**3.37**	**1.50**	**1.93**	**2.28**	**1.55**	**0.59**	**1.57**	**2.45**	**1.82**	**2.24**	**1.78**	**1.10**	**0.86**	**1.01**
Cycloaromatics (Indans, Tetralins,etc.)																		
cycloaromatic-C09	0.08	0.07	0.08	0.09	0.09	0.07	0.08	0.05	0.04	0.08	0.09	0.18	0.07	0.06	0.08	0.04	0.12	0.18
cycloaromatic-C10	0.50	0.43	0.63	0.65	0.72	0.47	1.01	0.43	0.57	0.51	0.67	1.05	0.41	0.41	0.60	0.33	0.49	0.95
cycloaromatic-C11	1.04	0.75	1.26	1.33	1.34	0.82	2.54	0.90	1.83	0.90	1.06	1.90	0.78	0.80	1.10	0.85	0.85	1.45
cycloaromatic-C12	1.33	0.91	1.38	1.46	1.67	0.88	2.62	1.12	2.89	0.78	1.05	1.97	0.95	0.96	1.11	1.34	1.00	1.02
cycloaromatic-C13	0.90	0.82	1.27	1.26	1.81	0.68	1.92	0.66	2.12	0.48	0.74	1.58	0.84	1.08	0.60	1.22	1.16	0.66
cycloaromatic-C14	0.29	0.30	0.64	0.64	0.95	0.25	0.97	0.09	0.58	0.14	0.20	0.75	0.20	0.35	0.09	0.33	1.02	0.26
cycloaromatics-C15+	0.07	0.12	0.37	0.37	0.50	0.09	0.82	<0.01	0.30	0.03	0.05	0.63	0.02	0.14	0.01	0.05	1.17	0.16
Total Cycloaromatics	**4.22**	**3.42**	**5.63**	**5.79**	**7.09**	**3.27**	**9.96**	**3.25**	**8.32**	**2.91**	**3.85**	**8.06**	**3.27**	**3.80**	**3.60**	**4.17**	**5.81**	**4.68**
Total Aromatics	**21.21**	**20.04**	**22.79**	**22.95**	**25.18**	**20.70**	**24.70**	**19.26**	**22.42**	**22.03**	**18.62**	**23.43**	**22.31**	**21.37**	**20.00**	**13.85**	**16.39**	**22.33**

Table A2-2a. Hydrocarbon Composition of CRC World Fuel Survey – Iso-Paraffins

POSF Number	3895	3896	3897	3898	3899	3900	3901	3902	3938	3939	3940	3941	3960	3961	3962	3963	3964	3965
Fuel Type	JP-8	JP-8	JP-8	JP-8	JET A	JP-8	JET A	JP-8	JP-8	JP-5	JP-5	JET A-1	JET A	JET A	JET A	JET A-1	JET A	JET A-1
World Survey Number	34	35	32	33	7	31	6	30	42	39	40	325	18	20	3	318	8	306
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
iso-Paraffins																		
C07 and lower-iso	0.15	0.08	0.14	0.07	0.02	0.31	0.10	0.19	0.11	0.05	0.05	0.17	0.39	0.06	0.19	0.11	0.20	0.26
C08-isoparaffins	0.40	0.13	0.58	0.36	0.18	0.51	0.23	0.58	0.39	0.15	0.03	0.53	0.60	0.71	0.37	0.37	0.59	0.82
C09-isoparaffins	0.95	3.94	1.76	0.84	0.48	1.60	0.59	1.61	1.50	0.57	0.21	1.51	0.99	1.95	0.86	1.75	2.01	1.98
C10-isoparaffins	3.31	6.87	4.12	2.98	1.61	6.34	2.08	5.35	4.00	1.70	1.42	5.00	2.59	2.36	3.13	7.50	4.79	5.53
C11-isoparaffins	4.88	4.80	5.89	4.73	3.13	6.03	3.79	6.84	6.55	3.07	3.83	6.10	3.57	2.78	4.57	8.35	5.28	4.87
C12-isoparaffins	3.73	3.08	6.57	4.09	6.21	4.43	5.17	5.51	6.70	3.67	3.47	4.23	3.01	2.07	4.16	3.83	4.10	3.29
C13-isoparaffins	3.74	2.43	6.43	3.76	6.24	4.13	4.98	4.87	6.45	3.62	3.14	3.71	2.74	1.93	4.17	2.61	3.75	2.99
C14-isoparaffins	3.67	2.05	4.43	3.42	4.87	3.46	4.23	3.82	4.32	3.65	3.41	2.19	2.80	1.66	3.79	2.37	3.30	3.04
C15-isoparaffins	2.54	1.52	3.26	1.44	3.24	2.26	3.30	2.34	2.34	2.98	2.27	0.64	1.88	1.00	2.83	1.29	2.37	1.72
C16-isoparaffins	0.67	0.70	0.76	0.20	1.12	0.68	1.17	0.71	0.56	0.82	0.78	0.13	0.86	0.46	1.22	0.33	0.96	0.45
C17-isoparaffins	0.18	0.27	0.15	0.03	0.28	0.16	0.33	0.20	0.14	0.06	0.21	0.06	0.34	0.22	0.43	0.07	0.44	0.13
C18-isoparaffins	0.04	0.07	0.04	<0.01	0.04	0.04	0.07	0.06	0.04	<0.01	0.06	0.03	0.14	0.11	0.13	0.01	0.22	0.04
C19-isoparaffins	<0.01	0.03	0.02	<0.01	<0.01	0.01	<0.01	0.03	0.02	<0.01	0.02	<0.01	0.04	0.05	0.04	<0.01	0.09	<0.01
C20-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.01	<0.01	0.03	<0.01
C21-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01
C22-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
C23-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
C24-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total iso-Paraffins	**24.25**	**25.98**	**34.16**	**21.94**	27.43	**29.96**	**26.03**	**32.14**	**33.13**	**20.35**	**18.91**	**24.32**	**19.95**	**15.40**	**25.90**	**28.59**	**28.15**	**25.12**

Table A2-2b. Hydrocarbon Composition of CRC World Fuel Survey – Iso-Paraffins (continued)

POSF Number	3966	3967	3968	3969	3970	3971	4108	4109	4110	4111	4152	4153	4154	4155	4156	4158	4159	4195	4197
Fuel Type	JET A-1	JET A-1	JP-8	JET A-1	JP-8	TS-1	JET A	JET A	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	Jet A-1	JET A-1	JP-8	JET A-1
World Survey Number	321	301	41	716	53	403	17	14	2	4	711	721	704	717	718	507	720	43	304
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
iso-Paraffins																			
C07 and lower-iso	0.16	0.25	0.21	0.23	0.25	0.05	0.16	0.12	0.19	0.21	0.30	0.03	0.18	0.22	0.40	0.04	0.04	0.05	0.26
C08-isoparaffins	0.71	0.75	0.36	0.79	0.51	0.55	0.73	0.30	0.50	0.64	0.70	0.09	0.73	0.61	0.65	0.24	0.02	0.14	0.83
C09-isoparaffins	3.04	2.70	1.40	2.70	1.34	0.92	3.11	0.89	1.88	1.43	2.15	1.90	3.18	2.57	1.18	0.76	1.55	0.53	2.69
C10-isoparaffins	5.97	5.73	4.02	5.42	4.25	2.72	4.54	3.20	5.38	4.46	5.75	2.75	7.56	7.11	4.39	5.99	2.81	2.33	5.45
C11-isoparaffins	5.40	6.01	6.33	5.57	6.03	5.80	4.17	4.41	5.47	4.91	5.81	10.79	6.51	5.98	6.55	19.03	11.92	5.04	5.54
C12-isoparaffins	4.03	4.43	5.90	3.81	5.43	12.91	3.42	3.93	4.09	3.66	3.97	9.32	4.58	4.33	12.76	16.13	10.07	5.17	4.18
C13-isoparaffins	3.44	3.94	4.64	3.10	4.72	4.99	3.23	4.04	3.71	3.45	3.33	1.19	3.49	4.05	4.18	8.52	1.25	5.08	3.70
C14-isoparaffins	2.84	3.00	3.05	2.59	4.00	3.14	2.82	3.63	3.04	3.09	2.89	0.79	2.14	3.31	2.49	3.55	0.70	4.32	3.00
C15-isoparaffins	1.70	1.64	1.53	1.55	2.77	1.07	2.26	2.65	2.00	2.35	0.94	0.06	1.17	1.92	0.64	1.46	0.03	3.08	1.86
C16-isoparaffins	0.46	0.47	0.49	0.31	1.02	0.19	1.50	1.01	0.66	1.13	0.09	<0.01	0.42	0.54	0.06	0.35	<0.01	1.32	0.57
C17-isoparaffins	0.15	0.12	0.21	0.09	0.36	0.06	0.95	0.43	0.28	0.70	0.02	<0.01	0.17	0.22	<0.01	0.08	<0.01	0.60	0.15
C18-isoparaffins	0.07	0.03	0.07	0.03	0.12	0.02	0.45	0.20	0.11	0.33	<0.01	<0.01	0.06	0.09	<0.01	0.02	<0.01	0.28	0.04
C19-isoparaffins	0.02	<0.01	0.02	<0.01	0.03	<0.01	0.21	0.07	0.03	0.07	<0.01	<0.01	0.03	0.03	<0.01	<0.01	<0.01	0.09	<0.01
C20-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
C21-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
C22-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
C23-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
C24-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total iso-Paraffins	**28.02**	**29.07**	**28.23**	**26.20**	**30.85**	**32.43**	**27.59**	**24.91**	**27.36**	**26.43**	**25.94**	**26.91**	**30.21**	**30.98**	**33.32**	**56.18**	**28.37**	**28.06**	**28.27**

Table A2-2c. Hydrocarbon Composition of CRC World Fuel Survey – Iso-Paraffins (continued)

POSF Number	4198	4324	4325	4326	4327	4363	4364	4365	4366	4368	4369	4370	4371	4384	4385	4386	4433	4461
Fuel Type	JET A-1	JET A-1	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1
World Survey Number	316	315	44	45	104	314	110	109	108	206	101	105	606	335	334	211	111	336
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
iso-Paraffins																		
C07 and lower-iso	0.28	0.32	0.24	0.21	0.02	0.23	0.02	0.08	0.21	0.37	0.12	0.29	0.35	0.24	0.19	0.16	0.18	0.08
C08-isoparaffins	0.74	0.66	0.43	0.43	0.13	0.61	<0.01	0.34	0.67	0.64	0.46	0.52	0.62	0.49	0.58	0.46	0.42	0.69
C09-isoparaffins	2.53	2.06	1.27	1.25	0.42	3.33	0.05	1.29	0.82	1.69	1.16	1.33	1.61	1.76	1.58	0.95	3.17	2.97
C10-isoparaffins	7.93	5.82	4.19	4.18	1.78	5.99	1.85	4.42	1.95	8.47	4.25	3.46	6.40	5.63	4.75	4.25	3.85	6.43
C11-isoparaffins	5.85	6.27	5.13	5.19	5.26	5.92	5.58	6.18	3.38	8.83	6.16	3.88	6.16	5.76	6.20	4.09	3.11	6.86
C12-isoparaffins	3.61	4.43	4.47	4.42	3.74	4.49	4.17	5.03	3.80	5.74	3.65	3.35	4.71	4.49	4.37	2.82	2.30	5.00
C13-isoparaffins	3.38	3.84	4.13	4.22	3.64	3.64	2.87	4.66	3.86	3.46	2.55	3.15	4.24	4.19	3.46	3.15	2.10	3.54
C14-isoparaffins	2.77	2.96	3.56	3.62	3.12	2.68	3.51	3.07	3.85	1.48	1.90	3.21	3.34	3.60	2.39	3.84	1.48	2.34
C15-isoparaffins	1.41	1.75	2.37	2.33	2.29	1.59	1.99	0.90	2.01	0.62	0.77	2.34	1.75	2.43	0.58	2.29	0.74	1.25
C16-isoparaffins	0.30	0.59	1.04	0.94	0.93	0.62	1.08	0.08	0.52	0.14	0.17	1.26	0.29	0.82	0.09	0.27	0.51	0.52
C17-isoparaffins	0.09	0.24	0.41	0.41	0.35	0.27	0.55	<0.01	0.26	0.03	0.06	0.80	0.03	0.23	0.03	0.07	0.27	0.26
C18-isoparaffins	0.04	0.09	0.16	0.16	0.11	0.11	0.28	<0.01	0.14	<0.01	0.03	0.36	<0.01	0.05	0.01	0.03	0.10	0.13
C19-isoparaffins	0.02	0.03	0.05	0.05	0.03	0.03	0.11	<0.01	0.06	<0.01	<0.01	0.18	<0.01	0.01	<0.01	<0.01	0.05	0.06
C20-isoparaffins	<0.01	<0.01	0.01	0.01	<0.01	<0.01	0.03	<0.01	0.02	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	0.03
C21-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02
C22-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
C23-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
C24-isoparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total iso-Paraffins	**28.97**	**29.06**	**27.46**	**27.44**	**21.81**	**29.51**	**22.10**	**26.06**	**21.57**	**31.48**	**21.27**	**24.18**	**29.51**	**29.72**	**24.22**	**22.38**	**18.29**	**30.19**

Table A2-3a. Hydrocarbon Composition of CRC World Fuel Survey – Normal Paraffins

POSF Number	3895	3896	3897	3898	3899	3900	3901	3902	3938	3939	3940	3941	3960	3961	3962	3963	3964	3965
Fuel Type	JP-8	JP-8	JP-8	JP-8	JET A	JP-8	JET A	JP-8	JP-8	JP-5	JP-5	JET A-1	JET A	JET A	JET A	JET A-1	JET A	JET A-1
World Survey Number	34	35	32	33	7	31	6	30	42	39	40	325	18	20	3	318	8	306
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
n-Paraffins																		
n-C07	0.08	0.03	0.07	0.05	0.01	0.18	0.04	0.18	0.08	0.02	<0.01	0.14	0.20	0.05	0.09	0.07	0.14	0.25
n-C08	0.43	0.21	0.64	0.41	0.15	0.63	0.22	0.72	0.54	0.23	0.06	0.74	0.66	0.60	0.37	0.49	0.58	1.08
n-C09	1.32	4.31	1.95	0.94	0.32	2.53	0.58	2.18	1.88	0.71	0.37	2.06	1.20	1.03	0.99	2.10	1.78	2.81
n-C10	3.59	3.62	3.53	2.56	0.70	5.29	1.45	5.08	3.75	1.56	2.27	5.34	2.62	1.04	2.49	7.42	3.10	4.71
n-C11	4.22	2.80	4.14	4.46	2.87	4.75	3.39	5.26	5.24	3.31	4.01	5.19	3.48	1.05	3.54	4.19	3.25	3.99
n-C12	3.49	1.93	3.64	3.71	4.19	3.95	3.88	4.34	4.61	3.34	3.50	4.19	3.00	0.81	3.27	2.58	2.78	3.28
n-C13	2.97	1.35	2.98	2.64	3.49	3.32	3.30	3.34	3.52	2.81	2.86	2.44	2.38	0.54	2.74	1.93	2.25	2.54
n-C14	2.23	1.05	2.04	1.34	2.61	2.31	2.62	2.16	1.95	2.32	2.09	0.74	1.76	0.39	2.09	1.30	1.64	1.58
n-C15	1.04	0.57	0.82	0.34	1.70	1.00	1.59	0.87	0.65	1.41	1.12	0.20	1.02	0.30	1.40	0.54	0.85	0.68
n-C16	0.24	0.27	0.17	0.05	0.50	0.23	0.53	0.22	0.16	0.12	0.33	0.07	0.47	0.19	0.53	0.09	0.30	0.20
n-C17	0.05	0.13	0.06	<0.01	0.06	0.07	0.09	0.08	0.06	0.01	0.08	0.03	0.17	0.10	0.15	0.02	0.15	0.05
n-C18	<0.01	0.02	0.02	<0.01	<0.01	0.02	0.01	0.03	0.02	<0.01	0.02	<0.01	0.04	0.04	0.03	<0.01	0.05	<0.01
n-C19	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.01	<0.01	0.02	<0.01
n-C20	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C21	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C22	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C23	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total n-Paraffins	**19.67**	**16.30**	**20.08**	**16.51**	16.61	**24.28**	**17.71**	**24.49**	**22.46**	**15.85**	**16.71**	**21.16**	**16.99**	**6.16**	**17.71**	**20.77**	**16.89**	**21.18**

Table A2-3b. Hydrocarbon Composition of CRC World Fuel Survey – Normal Paraffins (continued)

POSF Number	3966	3967	3968	3969	3970	3971	4108	4109	4110	4111	4152	4153	4154	4155	4156	4158	4159	4195	4197
Fuel Type	JET A-1	JET A-1	JP-8	JET A-1	JP-8	TS-1	JET A	JET A	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	Jet A-1	JET A-1	JP-8	JET A-1
World Survey Number	321	301	41	716	53	403	17	14	2	4	711	721	704	717	718	507	720	43	304
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
n-Paraffins																			
n-C07	0.15	0.19	0.14	0.16	0.17	0.08	0.11	0.05	0.13	0.16	0.18	0.01	0.16	0.17	0.25	0.06	<0.01	0.02	0.23
n-C08	1.04	0.84	0.46	1.39	0.55	0.57	0.68	0.29	0.67	0.67	0.89	0.78	1.12	0.82	0.86	0.34	0.27	0.17	0.93
n-C09	3.24	2.26	2.01	3.05	1.55	1.08	1.60	1.22	2.55	1.47	3.47	8.52	4.51	3.97	2.01	1.11	9.56	0.52	2.33
n-C10	3.71	3.50	3.70	5.18	3.46	3.49	2.04	2.63	4.00	3.42	6.50	<0.01	6.45	5.01	6.19	4.09	<0.01	1.85	3.41
n-C11	3.57	3.48	6.08	5.44	4.26	<0.01	2.22	3.76	4.01	3.52	6.81	<0.01	5.59	4.33	<0.01	3.34	<0.01	3.57	3.54
n-C12	2.97	2.86	5.13	4.24	3.14	6.48	1.89	3.72	3.31	3.07	5.83	6.70	4.14	3.54	6.48	2.89	6.66	3.43	2.98
n-C13	2.33	2.18	3.12	3.10	2.37	3.78	1.54	3.11	2.48	2.60	4.17	3.95	2.33	2.80	3.97	2.21	3.03	2.70	2.33
n-C14	1.66	1.39	1.66	2.02	2.07	1.39	1.27	2.20	1.71	1.99	1.79	0.24	1.06	1.82	1.23	1.26	0.03	1.92	1.61
n-C15	0.72	0.52	0.71	0.80	0.94	0.41	0.88	1.22	0.82	1.33	0.36	<0.01	0.44	0.59	0.20	0.45	<0.01	1.08	0.68
n-C16	0.20	0.14	0.26	0.22	0.33	0.11	0.57	0.52	0.30	0.76	0.06	<0.01	0.14	0.17	0.03	0.09	<0.01	0.56	0.18
n-C17	0.07	0.04	0.10	0.07	0.11	0.04	0.42	0.22	0.11	0.39	0.01	<0.01	0.05	0.09	<0.01	0.02	<0.01	0.24	0.04
n-C18	0.02	<0.01	0.03	0.01	0.03	<0.01	0.12	0.06	0.03	0.08	<0.01	<0.01	0.01	0.02	<0.01	<0.01	<0.01	0.07	<0.01
n-C19	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.03	0.02	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01
n-C20	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C21	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C22	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C23	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total n-Paraffins	**19.69**	**17.41**	**23.41**	**25.67**	**18.99**	**17.42**	**13.39**	**19.04**	**20.12**	**19.47**	**30.08**	**20.20**	**26.02**	**23.35**	**21.23**	**15.85**	**19.55**	**16.16**	**18.26**

Table A2-3c. Hydrocarbon Composition of CRC World Fuel Survey – Normal Paraffins (continued)

POSF Number	4198	4324	4325	4326	4327	4363	4364	4365	4366	4368	4369	4370	4371	4384	4385	4386	4433	4461
Fuel Type	JET A-1	JET A-1	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1
World Survey Number	316	315	44	45	104	314	110	109	108	206	101	105	606	335	334	211	111	336
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
n-Paraffins																		
n-C07	0.16	0.22	0.10	0.09	<0.01	0.16	<0.01	0.07	0.16	0.27	0.08	0.11	0.26	0.17	0.14	0.08	0.13	0.07
n-C08	0.74	0.83	0.43	0.42	0.18	0.97	<0.01	0.55	0.56	0.82	0.51	0.44	0.81	0.65	0.78	0.39	0.55	0.97
n-C09	3.49	2.41	1.45	1.43	0.48	3.67	0.20	1.95	0.89	2.76	1.19	1.07	3.06	2.63	2.05	1.15	1.48	2.84
n-C10	4.52	5.06	3.43	3.15	2.47	4.91	3.05	4.86	1.75	7.73	3.54	2.19	6.29	4.92	4.89	2.24	1.22	4.84
n-C11	1.83	4.53	3.74	3.78	3.35	4.79	5.18	5.78	4.73	6.57	3.79	3.07	5.64	4.71	5.19	2.30	1.03	4.80
n-C12	1.33	3.58	3.50	3.58	2.85	3.69	2.98	5.05	4.02	4.17	2.33	2.67	4.73	4.00	4.14	2.04	0.81	3.39
n-C13	0.98	2.56	2.74	2.85	2.34	2.51	1.69	3.43	3.25	1.75	1.13	2.20	3.85	3.31	2.33	1.80	0.60	2.09
n-C14	1.18	1.53	1.93	2.08	1.74	1.51	1.28	1.21	2.01	0.68	0.52	1.67	2.32	2.36	0.69	1.31	0.45	1.18
n-C15	0.48	0.64	1.16	1.16	1.07	0.67	0.89	0.18	0.74	0.25	0.18	1.05	0.60	1.10	0.14	0.36	0.30	0.60
n-C16	0.11	0.18	0.52	0.50	0.40	0.20	0.52	0.02	0.29	0.05	0.06	0.66	0.07	0.30	0.03	0.06	0.23	0.27
n-C17	0.04	0.08	0.21	0.21	0.13	0.07	0.26	<0.01	0.14	<0.01	0.02	0.50	<0.01	0.09	0.01	0.02	0.11	0.14
n-C18	0.02	0.01	0.05	0.05	0.02	0.01	0.07	<0.01	0.05	<0.01	<0.01	0.14	<0.01	0.02	<0.01	<0.01	0.03	0.05
n-C19	0.01	<0.01	0.02	0.02	<0.01	<0.01	0.03	<0.01	0.02	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	0.02
n-C20	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
n-C21	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C22	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
n-C23	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total n-Paraffins	**14.90**	**21.64**	**19.27**	**19.32**	**15.03**	**23.15**	**16.16**	**23.11**	**18.64**	**25.06**	**13.36**	**15.81**	**27.65**	**24.24**	**20.43**	**11.76**	**6.95**	**21.29**

Table A2-4a. Hydrocarbon Composition of CRC World Fuel Survey – Cyclo-Paraffins

POSF Number	3895	3896	3897	3898	3899	3900	3901	3902	3938	3939	3940	3941	3960	3961	3962	3963	3964	3965
Fuel Type	**JP-8**	**JP-8**	**JP-8**	**JP-8**	**JET A**	**JP-8**	**JET A**	**JP-8**	**JP-8**	**JP-5**	**JP-5**	**JET A-1**	**JET A**	**JET A**	**JET A**	**JET A-1**	**JET A**	**JET A-1**
World Survey Number	**34**	**35**	**32**	**33**	**7**	**31**	**6**	**30**	**42**	**39**	**40**	**325**	**18**	**20**	**3**	**318**	**8**	**306**
	Wt. %	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**	**Wt. %**
Monocycloparaffins																		
C07-monocyclocycloparaffins	0.22	0.06	0.12	0.27	0.08	0.18	0.11	0.11	0.07	0.07	0.01	0.38	0.61	0.27	0.19	0.14	0.23	0.58
C08-monocyclocycloparaffins	0.70	0.58	0.66	0.85	0.47	0.46	0.44	0.45	0.46	0.35	0.13	1.02	1.09	1.66	0.54	0.73	0.82	1.32
C09-monocyclocycloparaffins	2.16	4.59	1.69	2.04	1.16	1.80	1.09	1.43	1.53	1.07	0.77	2.64	2.27	5.10	1.27	2.95	2.60	3.23
C10-monocyclocycloparaffins	5.45	5.07	3.10	5.25	1.87	3.69	2.50	3.15	3.29	2.55	3.62	5.97	4.42	8.81	3.49	7.29	4.66	5.46
C11-monocyclocycloparaffins	6.44	4.61	4.58	7.59	5.08	3.80	5.07	3.56	4.59	5.54	7.28	6.52	5.94	10.26	4.80	5.00	5.19	5.10
C12-monocyclocycloparaffins	5.60	3.43	3.98	6.26	6.56	3.27	5.81	3.44	4.34	6.42	6.01	4.95	5.32	7.25	5.22	3.09	4.56	4.48
C13-monocyclocycloparaffins	4.75	2.52	2.72	3.78	4.88	2.65	4.26	2.77	2.62	5.68	5.24	2.67	4.19	4.80	3.87	2.19	3.09	3.32
C14-monocyclocycloparaffins	2.96	1.56	1.57	1.69	3.07	1.86	3.05	1.71	1.59	4.49	3.61	0.79	2.87	2.86	2.60	1.21	2.20	1.92
C15-monocyclocycloparaffins	1.38	0.99	0.45	0.44	1.82	0.75	1.86	0.63	0.47	2.30	1.80	0.21	1.90	1.66	1.67	0.48	1.18	0.82
C16-monocyclocycloparaffins	0.26	0.27	0.13	0.04	0.45	0.17	0.45	0.15	0.12	0.23	0.46	0.05	0.63	0.56	0.60	0.07	0.38	0.20
C17-monocyclocycloparaffins	0.06	0.14	0.04	<0.01	0.05	0.04	0.08	0.05	0.03	<0.01	0.13	0.02	0.20	0.16	0.16	0.01	0.18	0.05
C18-monocyclocycloparaffins	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	0.02	<0.01	0.05	0.04	0.02	<0.01	0.04	<0.01
C19+-monocyclocycloparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.02	<0.01	<0.01	0.02	<0.01
Total Monocycloparaffins	**29.98**	**23.84**	**19.03**	**28.21**	25.50	**18.67**	**24.72**	**17.47**	**19.11**	**28.72**	**29.10**	**25.21**	**29.51**	**43.46**	**24.47**	**23.16**	**25.15**	**26.48**
Dicycloparaffins																		
C08-dicycloparaffins	0.03	0.08	0.02	0.04	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.05	0.05	0.06	0.02	0.03	0.03	0.06
C09-dicycloparaffins	0.65	0.96	0.29	0.59	0.18	0.37	0.21	0.25	0.33	0.32	0.35	0.85	0.81	1.24	0.26	0.64	0.54	0.85
C10-dicycloparaffins	1.51	1.11	0.59	1.19	0.70	0.45	0.77	0.47	0.53	0.72	1.45	1.44	1.19	2.46	0.85	1.46	1.42	0.94
C11-dicycloparaffins	2.05	1.56	1.16	3.38	2.91	0.82	2.43	0.89	1.14	2.27	2.54	2.16	2.17	4.32	1.94	1.29	2.12	1.49
C12-dicycloparaffins	2.08	1.61	0.97	3.73	3.43	0.80	2.70	0.72	0.80	2.70	2.97	2.02	2.29	4.32	2.01	1.07	1.84	1.74
C13-dicycloparaffins	1.80	1.29	0.72	2.63	2.24	0.77	2.21	0.78	0.75	4.79	2.68	0.98	2.04	4.73	2.00	0.78	1.97	1.45
C14-dicycloparaffins	0.96	0.98	0.26	1.43	1.60	0.48	2.18	0.35	0.22	2.55	1.41	0.37	1.29	2.28	1.63	0.48	1.02	0.89
C15-dicycloparaffins	0.14	0.21	0.03	0.20	0.29	0.05	0.48	0.05	0.03	0.51	0.45	0.05	0.44	0.76	0.51	0.09	0.30	0.17
C16-dicycloparaffins	0.01	0.07	<0.01	<0.01	0.03	<0.01	0.02	<0.01	<0.01	0.01	0.08	<0.01	0.06	0.11	0.02	<0.01	0.08	0.02
C17+-dicycloparaffins	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	0.03	0.04	0.02	<0.01	0.03	<0.01
Total Dicycloparaffins	**9.23**	**7.88**	**4.03**	**13.20**	11.41	**3.78**	**11.01**	**3.54**	**3.82**	**13.90**	**11.97**	**7.92**	**10.38**	**20.31**	**9.26**	**5.85**	**9.36**	**7.60**
Tricycloparaffins																		
C10-tricycloparaffins	<0.01	0.01	<0.01	0.05	0.01	<0.01	0.01	<0.01	<0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0.01	0.01
C11-tricycloparaffins	0.04	0.07	0.06	0.25	0.11	0.05	0.12	0.04	0.04	0.10	0.11	0.11	0.09	0.13	0.10	0.05	0.07	0.06
C12-tricycloparaffins	<0.01	0.06	<0.01	0.05	0.02	<0.01	0.02	<0.01	<0.01	0.07	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01
Total Tricycloparaffins	**0.04**	**0.15**	**0.06**	**0.34**	0.15	**0.06**	**0.15**	**0.04**	**0.05**	**0.19**	**0.13**	**0.13**	**0.10**	**0.18**	**0.11**	**0.06**	**0.08**	**0.07**
Total Cycloparaffins	**39.26**	**31.87**	**23.12**	**41.75**	37.06	**22.50**	**35.88**	**21.04**	**22.98**	**42.80**	**41.20**	**33.26**	**39.98**	**63.95**	**33.84**	**29.07**	**34.58**	**34.15**

Table A2-4b. Hydrocarbon Composition of CRC World Fuel Survey – Cyclo-Paraffins (continued)

POSF Number	3966	3967	3968	3969	3970	3971	4108	4109	4110	4111	4152	4153	4154	4155	4156	4158	4159	4195	4197
Fuel Type	JET A-1	JET A-1	JP-8	JET A-1	JP-8	TS-1	JET A	JET A	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	mi-syn	JET A-1	JP-8	JET A-1
World Survey Number	321	301	41	716	53	403	17	14	2	4	711	721	704	717	718	507	720	43	304
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
Monocycloparaffins																			
C07-monocyclocycloparaffins	0.40	0.34	0.18	0.56	0.20	0.23	0.39	0.13	0.18	0.48	0.54	0.02	0.18	0.25	0.84	0.09	<0.01	0.08	0.45
C08-monocyclocycloparaffins	1.50	1.23	0.51	1.92	0.51	0.69	1.38	0.43	0.66	0.87	0.99	0.96	0.87	0.70	1.26	0.28	0.41	0.29	1.26
C09-monocyclocycloparaffins	3.90	3.56	1.97	3.19	1.49	1.39	4.13	1.58	2.30	1.77	2.61	5.14	3.26	2.78	2.06	0.93	4.69	0.90	3.19
C10-monocyclocycloparaffins	4.91	5.48	4.03	4.35	3.29	3.88	5.13	3.85	4.52	3.97	4.41	5.77	4.66	4.01	4.36	2.50	5.64	3.41	4.52
C11-monocyclocycloparaffins	4.44	5.37	5.35	4.02	4.53	7.24	5.78	5.07	4.75	3.99	3.73	4.19	4.34	3.97	5.06	1.97	4.11	5.85	4.71
C12-monocyclocycloparaffins	3.51	4.20	4.29	2.71	4.30	6.40	4.26	4.94	4.45	3.58	2.71	2.78	3.31	3.38	3.55	1.52	2.53	6.17	3.97
C13-monocyclocycloparaffins	2.92	3.04	2.71	1.74	3.27	3.61	3.22	3.78	3.24	2.68	1.70	1.52	2.16	2.49	2.04	1.80	1.15	4.87	3.09
C14-monocyclocycloparaffins	1.64	1.66	1.27	0.95	2.10	1.20	2.23	2.40	2.05	1.90	0.65	0.20	1.01	1.55	0.58	1.27	0.09	3.51	1.85
C15-monocyclocycloparaffins	0.73	0.61	0.62	0.40	1.11	0.35	1.52	1.44	1.00	1.22	0.14	<0.01	0.45	0.54	0.09	0.51	<0.01	2.17	0.83
C16-monocyclocycloparaffins	0.18	0.13	0.19	0.08	0.35	0.07	0.75	0.51	0.29	0.56	0.01	<0.01	0.12	0.16	<0.01	0.08	<0.01	0.92	0.18
C17-monocyclocycloparaffins	0.06	0.04	0.06	0.02	0.10	0.02	0.33	0.22	0.11	0.27	<0.01	<0.01	0.04	0.05	<0.01	0.01	<0.01	0.42	0.04
C18-monocyclocycloparaffins	0.01	<0.01	0.01	<0.01	0.02	<0.01	0.10	0.07	0.02	0.05	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01	0.11	<0.01
C19+-monocyclocycloparaffins	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.03	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.05	<0.01
Total Monocycloparaffins	**24.21**	**25.66**	**21.21**	**19.93**	**21.28**	**25.08**	**29.26**	**24.43**	**23.57**	**21.35**	**17.51**	**20.57**	**20.43**	**19.91**	**19.87**	**10.96**	**18.63**	**28.73**	**24.09**
Dicycloparaffins																			
C08-dicycloparaffins	0.07	0.05	0.02	0.07	0.02	0.02	0.04	0.02	0.03	0.03	0.04	0.05	0.03	0.03	0.04	0.01	0.04	0.01	0.04
C09-dicycloparaffins	1.01	0.84	0.36	0.84	0.30	0.36	0.82	0.52	0.53	0.49	0.76	1.94	0.76	0.65	0.69	0.21	1.84	0.20	0.74
C10-dicycloparaffins	0.80	1.50	0.69	1.14	0.60	1.19	1.68	1.05	0.92	1.01	0.84	3.14	0.89	0.77	1.62	0.25	2.57	0.73	1.15
C11-dicycloparaffins	1.32	1.66	1.71	1.62	1.22	2.30	1.84	2.13	1.51	1.88	1.53	3.59	1.25	1.09	2.20	0.86	2.95	1.89	1.42
C12-dicycloparaffins	1.41	1.44	1.53	1.86	1.16	1.94	1.69	2.27	1.82	2.15	1.51	1.93	0.95	1.06	2.37	0.86	1.73	2.30	1.29
C13-dicycloparaffins	0.96	1.13	0.94	1.15	1.08	1.13	1.62	1.89	1.21	1.86	0.94	0.46	0.57	0.96	0.85	0.82	0.41	1.98	1.05
C14-dicycloparaffins	0.70	0.48	0.57	0.98	0.89	0.39	1.14	1.67	0.89	2.10	0.66	0.02	0.32	0.56	0.42	0.53	0.02	1.39	0.68
C15-dicycloparaffins	0.09	0.09	0.11	0.15	0.18	0.06	0.38	0.42	0.15	0.71	0.05	<0.01	0.05	0.06	0.03	0.11	<0.01	0.46	0.07
C16-dicycloparaffins	0.02	0.01	0.02	0.01	0.01	<0.01	0.05	0.07	0.01	0.10	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01	0.05	0.01
C17+-dicycloparaffins	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.04	0.02	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04	<0.01
Total Dicycloparaffins	**6.37**	**7.21**	**5.96**	**7.83**	**5.47**	**7.40**	**9.29**	**10.08**	**7.09**	**10.37**	**6.33**	**11.14**	**4.83**	**5.22**	**8.23**	**3.66**	**9.56**	**9.06**	**6.48**
Tricycloparaffins																			
C10-tricycloparaffins	<0.01	0.01	0.06	0.03	<0.01	<0.01	0.02	0.01	<0.01	0.02	0.03	<0.01	<0.01	0.01	0.04	0.02	<0.01	0.03	<0.01
C11-tricycloparaffins	0.07	0.07	0.29	0.16	0.06	0.08	0.09	0.10	0.07	0.15	0.23	<0.01	0.05	0.07	0.23	0.06	0.01	0.16	0.05
C12-tricycloparaffins	<0.01	0.06	0.03	0.02	<0.01	0.06	0.03	<0.01	<0.01	0.05	0.08	<0.01	<0.01	<0.01	0.03	<0.01	<0.01	0.03	<0.01
Total Tricycloparaffins	**0.08**	**0.14**	**0.38**	**0.22**	**0.07**	**0.15**	**0.14**	**0.12**	**0.08**	**0.22**	**0.34**	**<0.01**	**0.06**	**0.09**	**0.29**	**0.08**	**0.01**	**0.21**	**0.06**
Total Cycloparaffins	**30.66**	**33.00**	**27.54**	**27.98**	**26.82**	**32.64**	**38.69**	**34.63**	**30.74**	**31.94**	**24.18**	**31.72**	**25.31**	**25.21**	**28.39**	**14.69**	**28.20**	**38.00**	**30.62**

Table A2-4c. Hydrocarbon Composition of CRC World Fuel Survey – Cyclo-Paraffins (continued)

POSF Number	4198	4324	4325	4326	4327	4363	4364	4365	4366	4368	4369	4370	4371	4384	4385	4386	4433	4461
Fuel Type	JET A-1	JET A-1	JET A	JET A	JET A-1	JET A-1	JET A-1	JET A	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1	JET A-1
World Survey Number	316	315	44	45	104	314	110	109	108	206	101	105	606	335	334	211	111	336
	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %	Wt. %
Monocycloparaffins																		
C07-monocyclocycloparaffins	0.23	0.40	0.19	0.19	0.04	0.29	<0.01	0.20	0.39	0.13	0.30	0.28	0.19	0.17	0.37	0.32	0.14	0.14
C08-monocyclocycloparaffins	0.89	0.93	0.58	0.61	0.31	1.09	0.01	0.75	0.90	0.47	1.09	0.96	0.52	0.54	1.15	0.86	1.74	0.97
C09-monocyclocycloparaffins	4.11	2.65	1.72	1.74	0.99	3.20	0.45	2.28	1.70	1.76	3.19	2.48	1.87	2.04	2.84	3.76	7.17	3.02
C10-monocyclocycloparaffins	6.55	4.82	3.66	3.78	4.53	4.37	4.77	5.01	3.06	4.73	8.93	4.40	3.66	3.86	6.31	9.03	9.43	4.60
C11-monocyclocycloparaffins	5.28	4.74	4.73	4.53	6.87	4.55	7.53	6.06	6.67	4.56	9.73	5.73	3.41	3.99	7.13	7.86	7.63	4.79
C12-monocyclocycloparaffins	4.19	4.30	4.55	4.70	6.38	3.48	5.28	5.57	6.54	3.29	5.64	4.84	3.17	3.71	5.35	6.35	5.75	3.51
C13-monocyclocycloparaffins	3.04	3.00	3.32	3.30	4.70	2.63	3.64	3.64	5.17	1.75	2.56	3.84	2.54	2.95	2.79	5.23	4.04	2.24
C14-monocyclocycloparaffins	1.46	1.75	2.19	2.06	3.17	1.38	2.67	1.22	2.86	0.71	0.97	2.65	1.39	1.87	0.78	3.01	2.51	1.07
C15-monocyclocycloparaffins	0.53	0.77	1.33	1.27	1.70	0.62	2.02	0.22	1.08	0.30	0.33	1.62	0.35	0.87	0.16	0.87	1.76	0.54
C16-monocyclocycloparaffins	0.10	0.22	0.44	0.47	0.58	0.15	1.03	0.01	0.28	0.06	0.08	0.74	0.03	0.18	0.03	0.10	0.97	0.21
C17-monocyclocycloparaffins	0.04	0.07	0.20	0.19	0.18	0.06	0.59	<0.01	0.15	0.01	0.02	0.43	<0.01	0.05	<0.01	0.03	0.42	0.11
C18-monocyclocycloparaffins	0.01	0.01	0.03	0.04	0.03	<0.01	0.17	<0.01	0.05	<0.01	<0.01	0.12	<0.01	<0.01	<0.01	<0.01	0.13	0.04
C19+-monocyclocycloparaffins	0.01	<0.01	0.02	0.01	<0.01	<0.01	0.10	<0.01	0.03	<0.01	<0.01	0.05	<0.01	<0.01	<0.01	<0.01	0.02	0.04
Total Monocycloparaffins	**26.45**	**23.66**	**22.95**	**22.89**	**29.48**	**21.84**	**28.28**	**24.96**	**28.86**	**17.76**	**32.84**	**28.12**	**17.14**	**20.24**	**26.93**	**37.43**	**41.71**	**21.29**
Dicycloparaffins																		
C08-dicycloparaffins	0.05	0.03	0.02	0.02	0.01	0.05	<0.01	0.04	0.03	0.02	0.06	0.03	0.02	0.02	0.05	0.03	0.04	0.04
C09-dicycloparaffins	1.21	0.52	0.40	0.43	0.20	0.70	0.17	0.60	0.36	0.37	1.30	0.61	0.36	0.46	0.94	0.70	1.34	0.62
C10-dicycloparaffins	1.47	0.89	0.85	0.90	1.11	0.80	1.15	0.97	0.81	0.64	3.67	1.15	0.59	0.60	1.58	1.23	3.27	0.88
C11-dicycloparaffins	1.67	1.24	1.52	1.61	2.02	1.17	2.14	1.76	2.15	0.90	3.92	1.79	0.86	1.02	2.41	3.03	4.04	1.24
C12-dicycloparaffins	1.73	1.23	1.44	1.49	1.73	0.94	1.70	1.80	2.23	0.75	2.83	1.69	0.71	0.94	2.12	3.60	2.84	0.96
C13-dicycloparaffins	1.24	0.90	1.77	1.55	1.95	0.65	1.86	1.10	1.90	0.53	1.32	1.61	0.50	0.87	0.96	3.67	2.62	0.63
C14-dicycloparaffins	0.82	0.59	1.06	1.02	1.00	0.35	1.09	0.27	0.75	0.35	0.58	1.08	0.27	0.41	0.24	1.78	1.51	0.37
C15-dicycloparaffins	0.16	0.11	0.24	0.24	0.33	0.07	0.42	0.02	0.16	0.07	0.10	0.31	0.02	0.06	0.02	0.18	0.60	0.09
C16-dicycloparaffins	<0.01	0.02	0.02	0.02	0.03	0.02	0.05	<0.01	0.02	<0.01	0.01	0.06	<0.01	<0.01	<0.01	0.02	0.12	<0.01
C17+-dicycloparaffins	<0.01	<0.01	0.02	0.02	0.02	<0.01	0.07	<0.01	0.03	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	0.08	0.01
Total Dicycloparaffins	**8.37**	**5.54**	**7.36**	**7.31**	**8.41**	**4.75**	**8.66**	**6.55**	**8.46**	**3.65**	**13.80**	**8.37**	**3.33**	**4.39**	**8.33**	**14.26**	**16.46**	**4.86**
Tricycloparaffins																		
C10-tricycloparaffins	0.01	<0.01	0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	0.02	0.01	<0.01	<0.01	0.02	0.03	0.02	<0.01
C11-tricycloparaffins	0.07	0.05	0.08	0.08	0.08	0.05	0.08	0.06	0.05	0.03	0.09	0.07	0.05	0.03	0.09	0.17	0.12	0.04
C12-tricycloparaffins	<0.01	<0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.11	0.04	<0.01
Total Tricycloparaffins	**0.09**	**0.06**	**0.16**	**0.10**	**0.09**	**0.06**	**0.09**	**0.07**	**0.05**	**0.03**	**0.11**	**0.08**	**0.06**	**0.04**	**0.10**	**0.31**	**0.18**	**0.05**
Total Cycloparaffins	**34.91**	**29.26**	**30.47**	**30.30**	**37.98**	**26.64**	**37.03**	**31.58**	**37.37**	**21.44**	**46.75**	**36.58**	**20.53**	**24.67**	**35.36**	**52.00**	**58.36**	**26.20**

List of Symbols, Abbreviations, and Acronyms

Acronym	Description
AFRL	Air Force Research Laboratory
APFEERD	Airbreathing Propulsion Fuels and Energy Exploratory Research and Development
ATJ	Alcohol to Jet
CAAFI	Commercial Aviation Alternate Fuels Initiative
CH	Catalytic Hydrothermolysis
CRC	Coordinating Research Council
DoD	Department of Defense
EASA	European Aviation Safety Agency
FSJF	Sasol Fully Synthetic Jet Fuel
F-T	Fischer-Tropsch
HDCJ	Hydrotreated Depolymerized Cellulosic Jet
HEFA	Hydrotreated Esters and Fatty Acids
IPK	Iso-Paraffinic Kerosene
KF 831	Metrohm Karl Fischer Coulometer
NIST	National Institute of Standards and Testing
OEM	Original Equipment Manufacturer
R4RQ	Research for the Aerospace Systems Directorate
RQ	Aerospace Systems Directorate
RQT	Turbine Engine Division
RQTF	Fuels and Energy Branch
SIM	Selected Ion Monitoring Mode
SKA	Synthesized Kerosenes with Aromatics
SPK	Synthesized Paraffinic Kerosenes
UDRI	University of Dayton Research Institute
USAF	United States Air Force
UTC	Universal Technology Corporation
WFS	World Fuel Survey
WPAFB	Wright-Patterson Air Force Base